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(54) **SOLID-STATE THERMAL SWITCH PANEL FOR THERMAL STORAGE**

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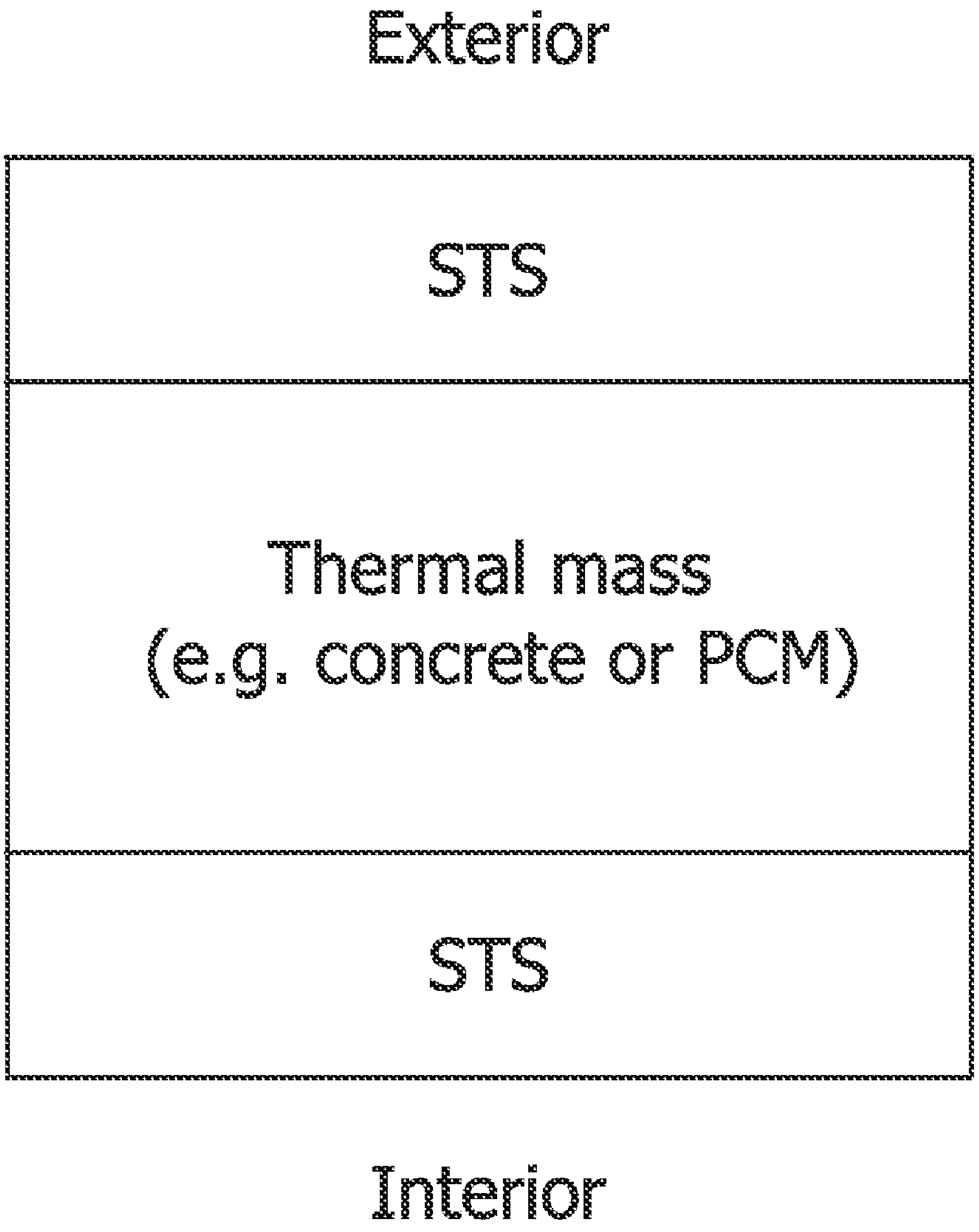
CPC ***H01H 37/585*** (2013.01)

(57) **ABSTRACT**

Systems and method for operating an STS panel comprising: a filler with a thermally resistive/insulating material and a first open area (FOA); first and second layers of thermally conductive material (TCM) that are spaced apart, extend parallel, and sandwich the filler such that FOA extends from the first layer of TCM to the second layer of TCM; and a first thermal connector (FTC) disposed in FOA (a) so as to reside between and be spaced apart from the filler, and (b) so as to reside between and be in contact with the first and second layers of TCM. FTC is switchable between a first position in which a thermal bridge is created to allow heat transfer between the first and second layers of TCM and a second position in which the thermal bridge is broken and a thermal gap is created to prevent the heat transfer.



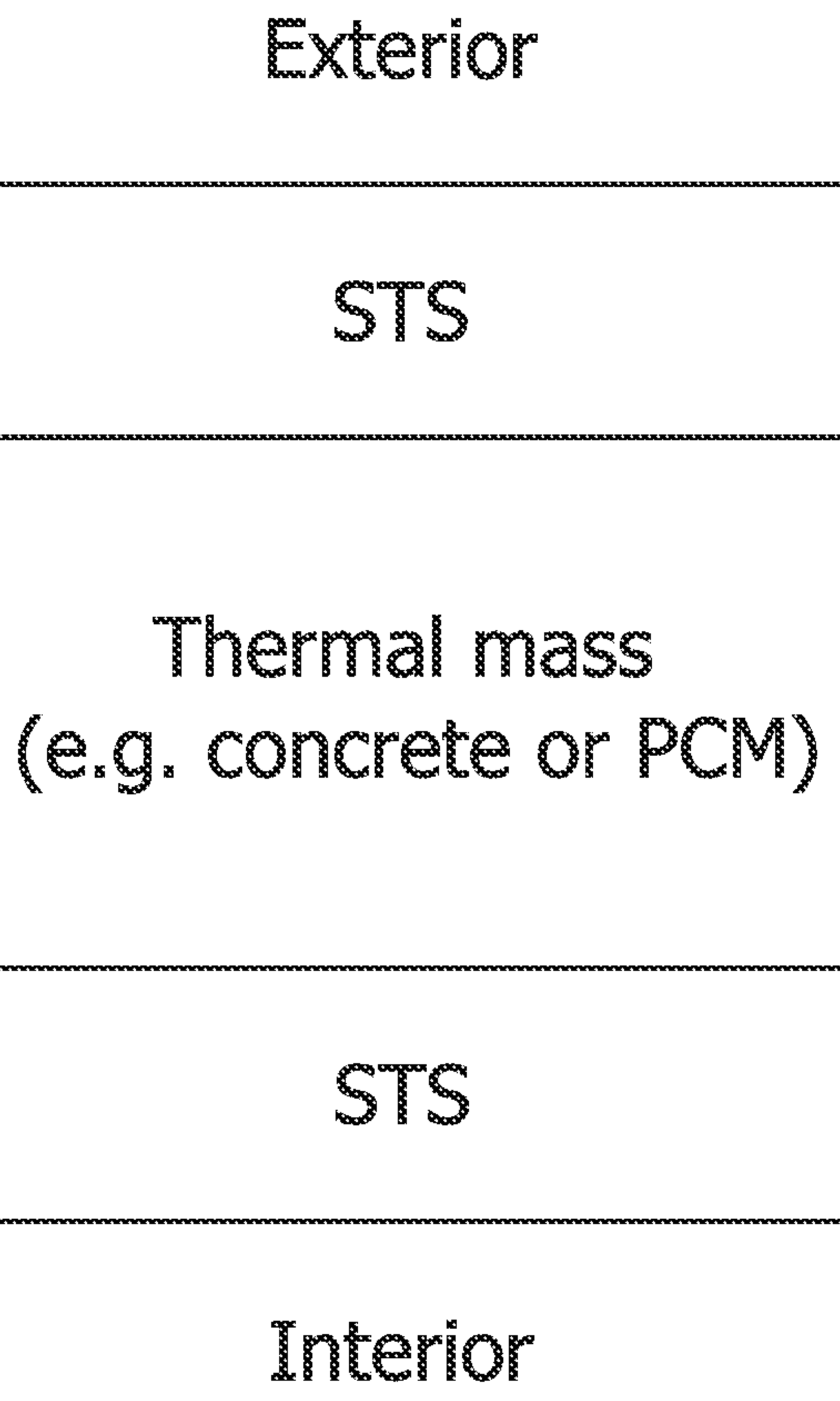


FIG. 1

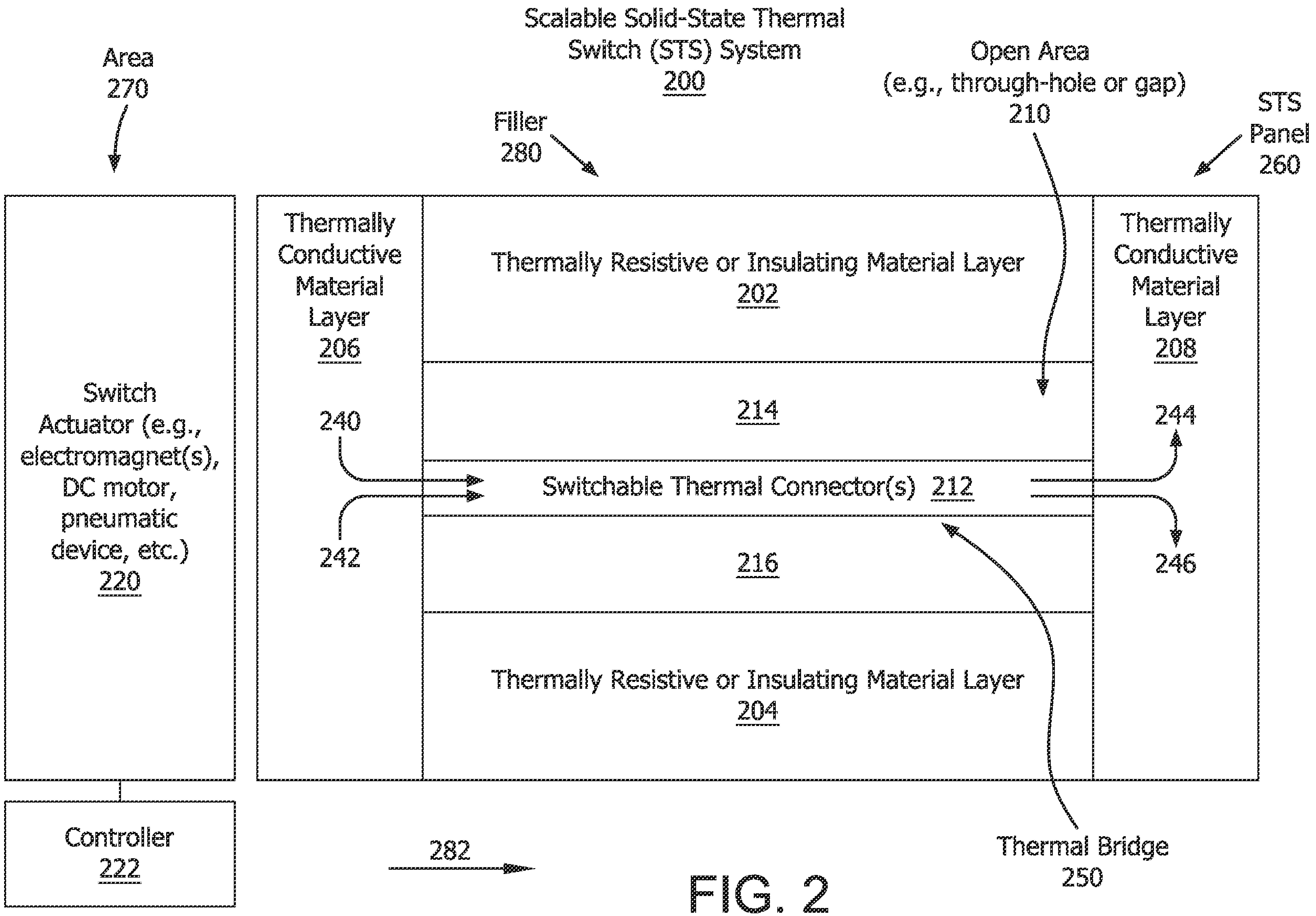


FIG. 2
(ON or Low-R state)

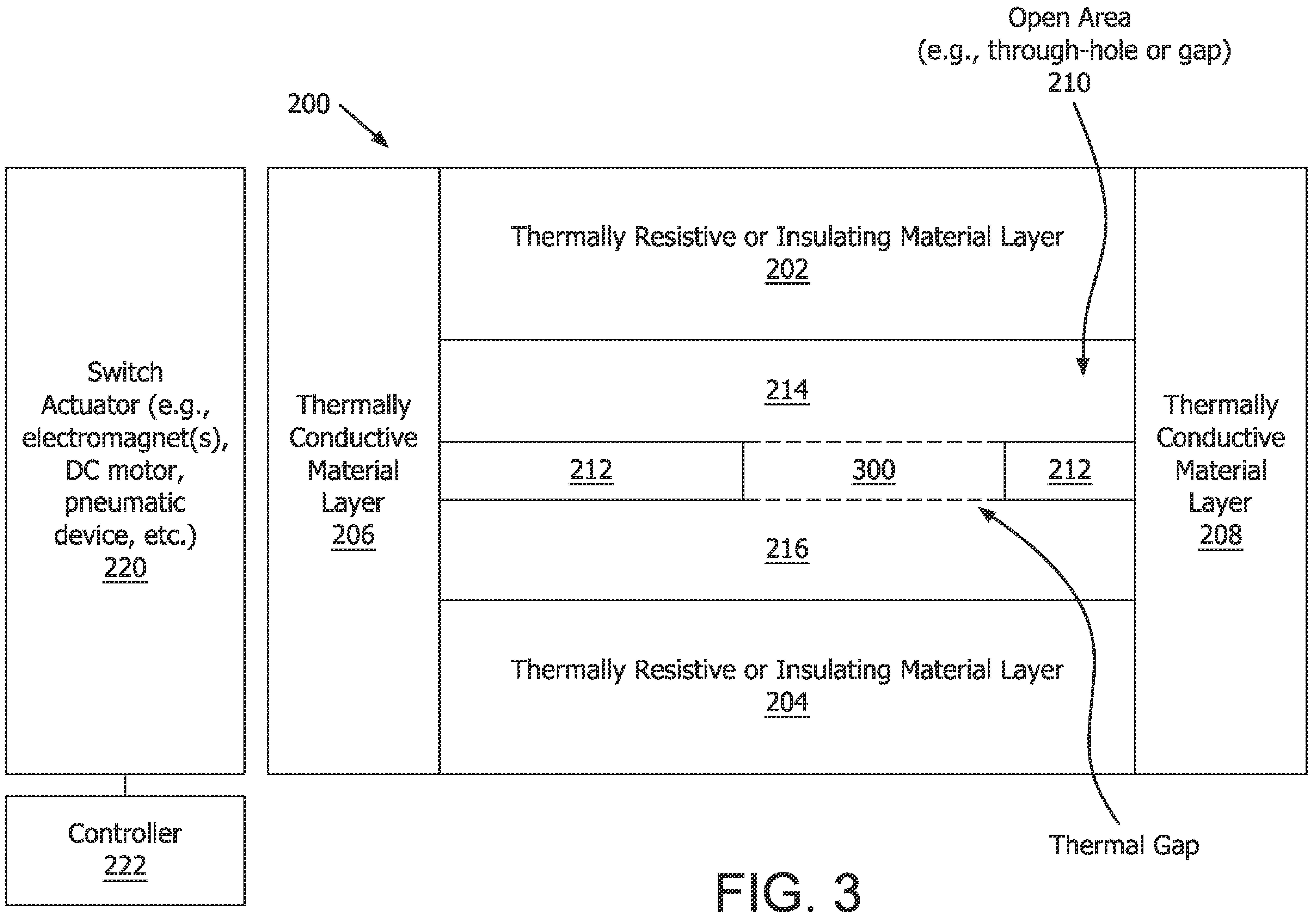


FIG. 3
(OFF or High-R state)

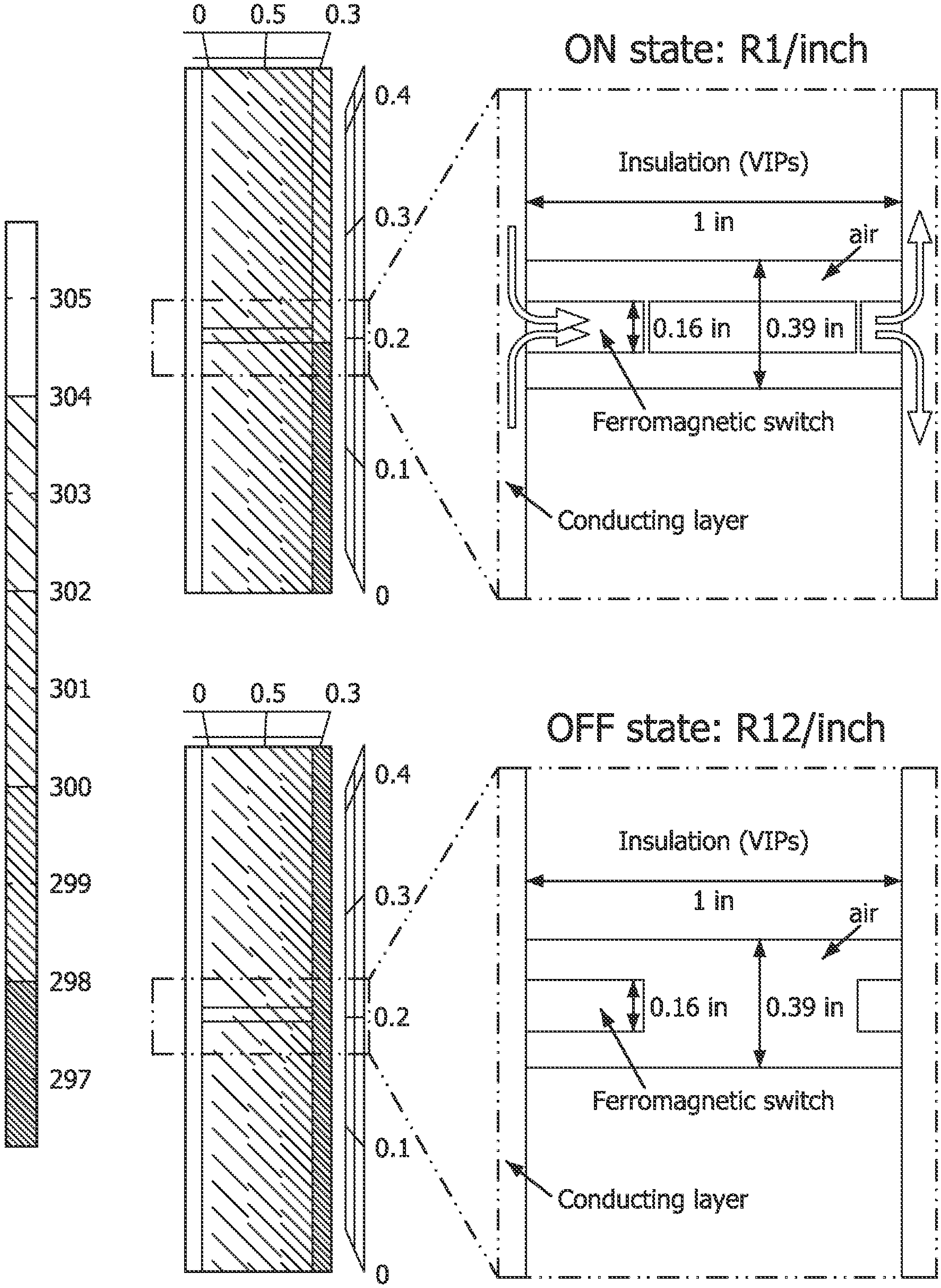

0
0.5
0.3
ON state: R1/inch
0.4
0.3
0.2
0.1
0
305
304
303
302
301
300
299
298
297
Insulation (VIPs)
1 in
air
0.16 in
0.39 in
Ferromagnetic switch
Conducting layer
0
0.5
0.3
OFF state: R12/inch
0.4
0.3
0.2
0.1
0
Insulation (VIPs)
1 in
air
0.16 in
0.39 in
Ferromagnetic switch
Conducting layer

FIG. 4

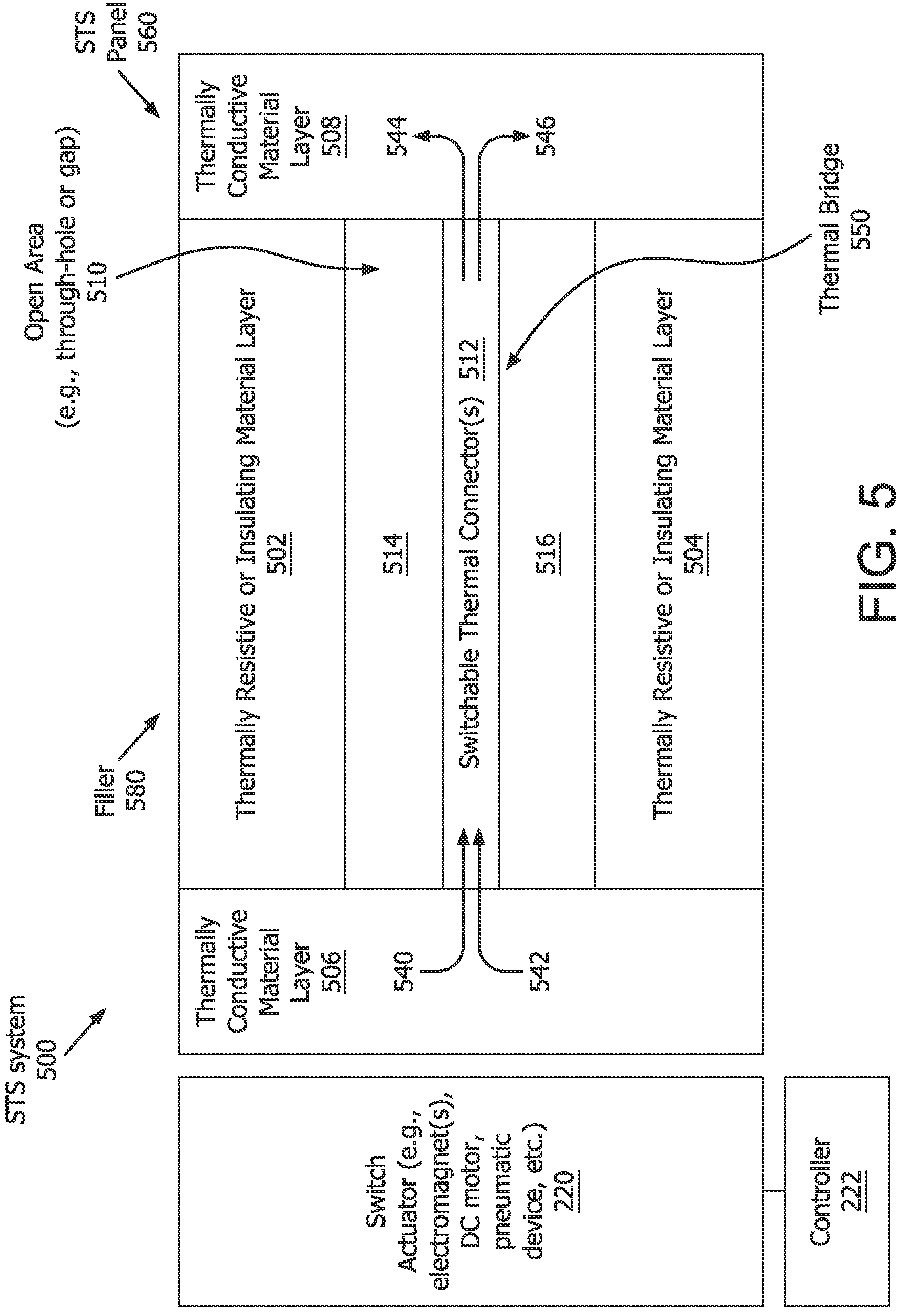


FIG. 5
(ON or Low-R state)

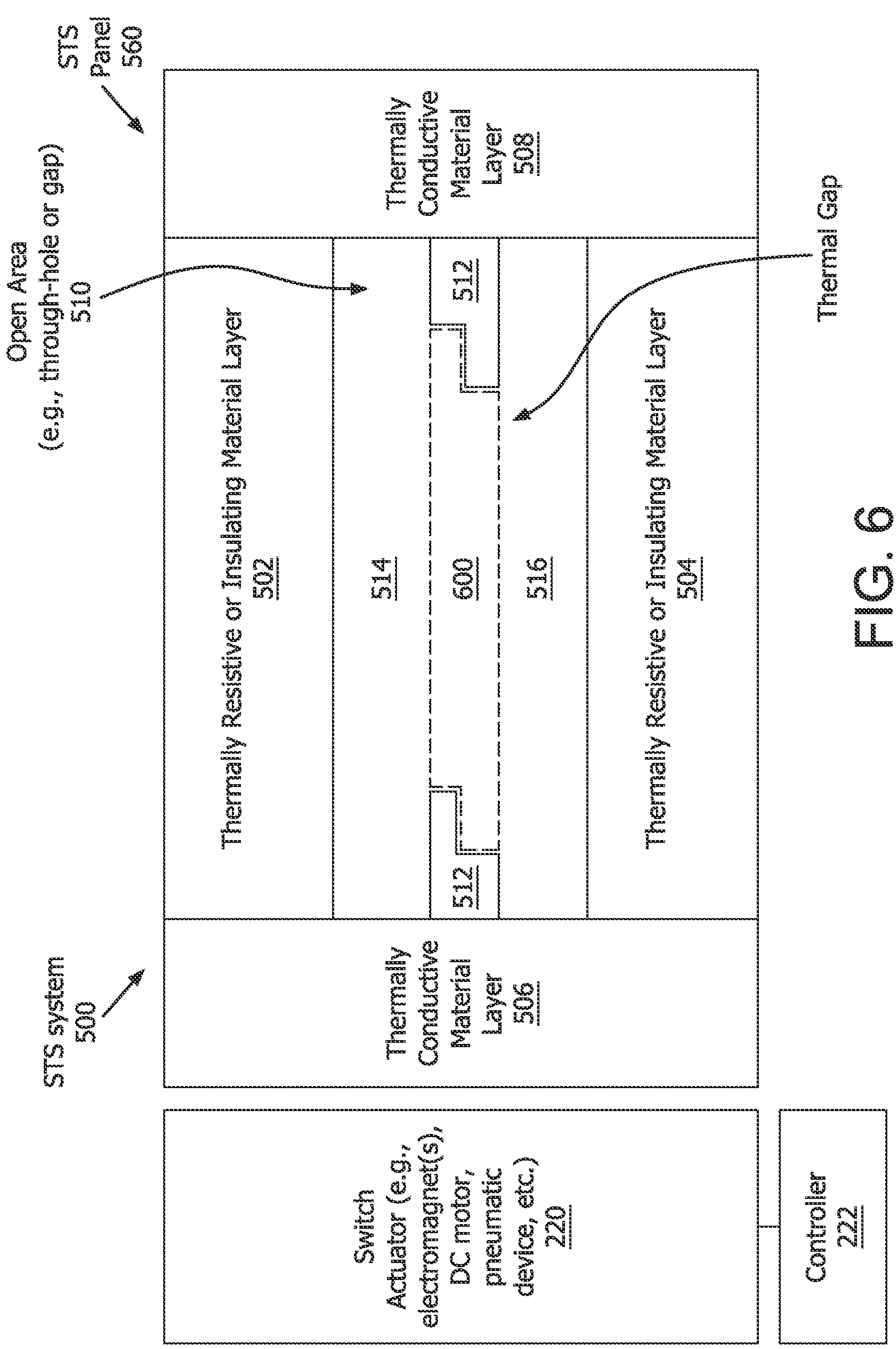


FIG. 6
(OFF or High-R state)

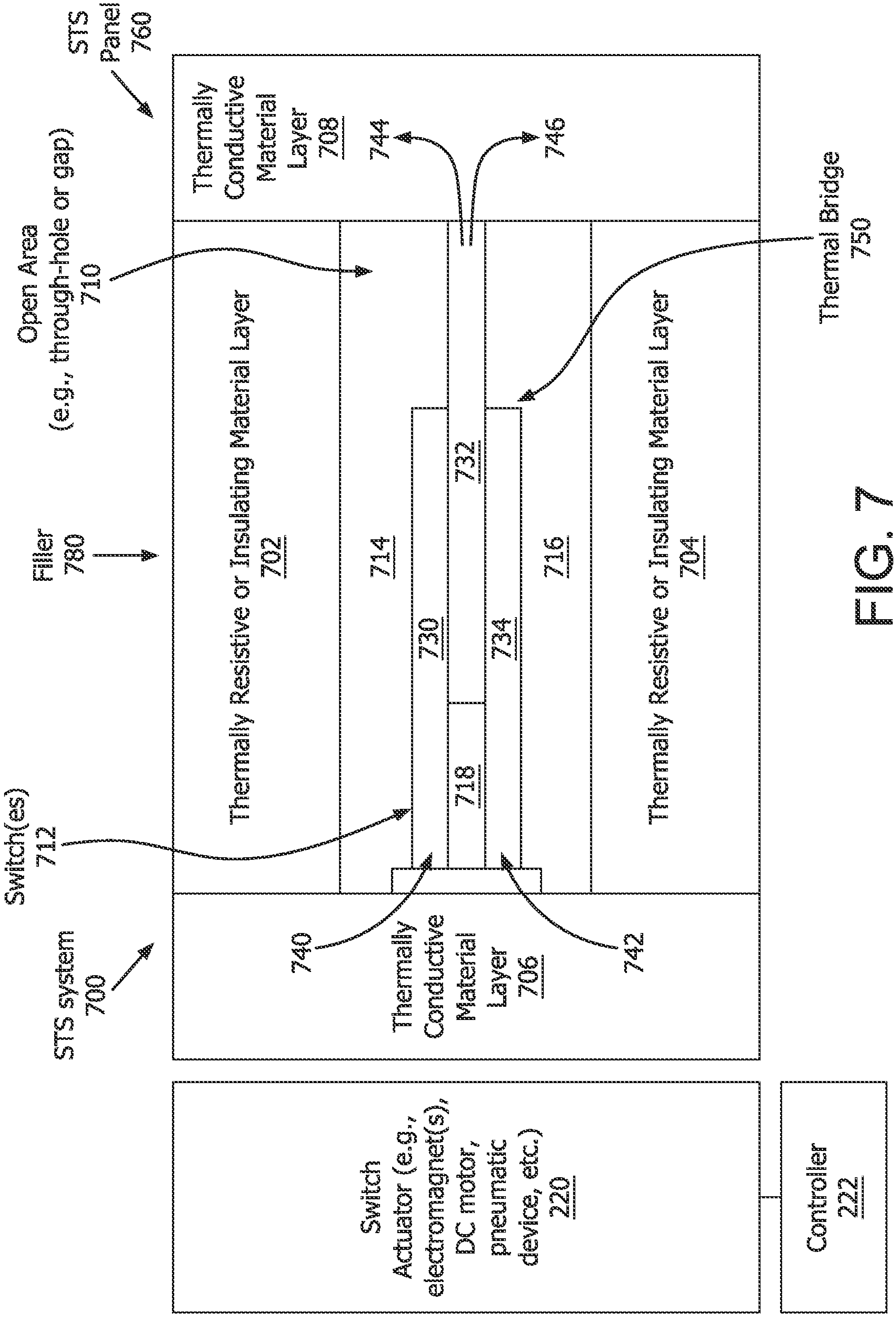


FIG. 7
(ON or Low-R state)

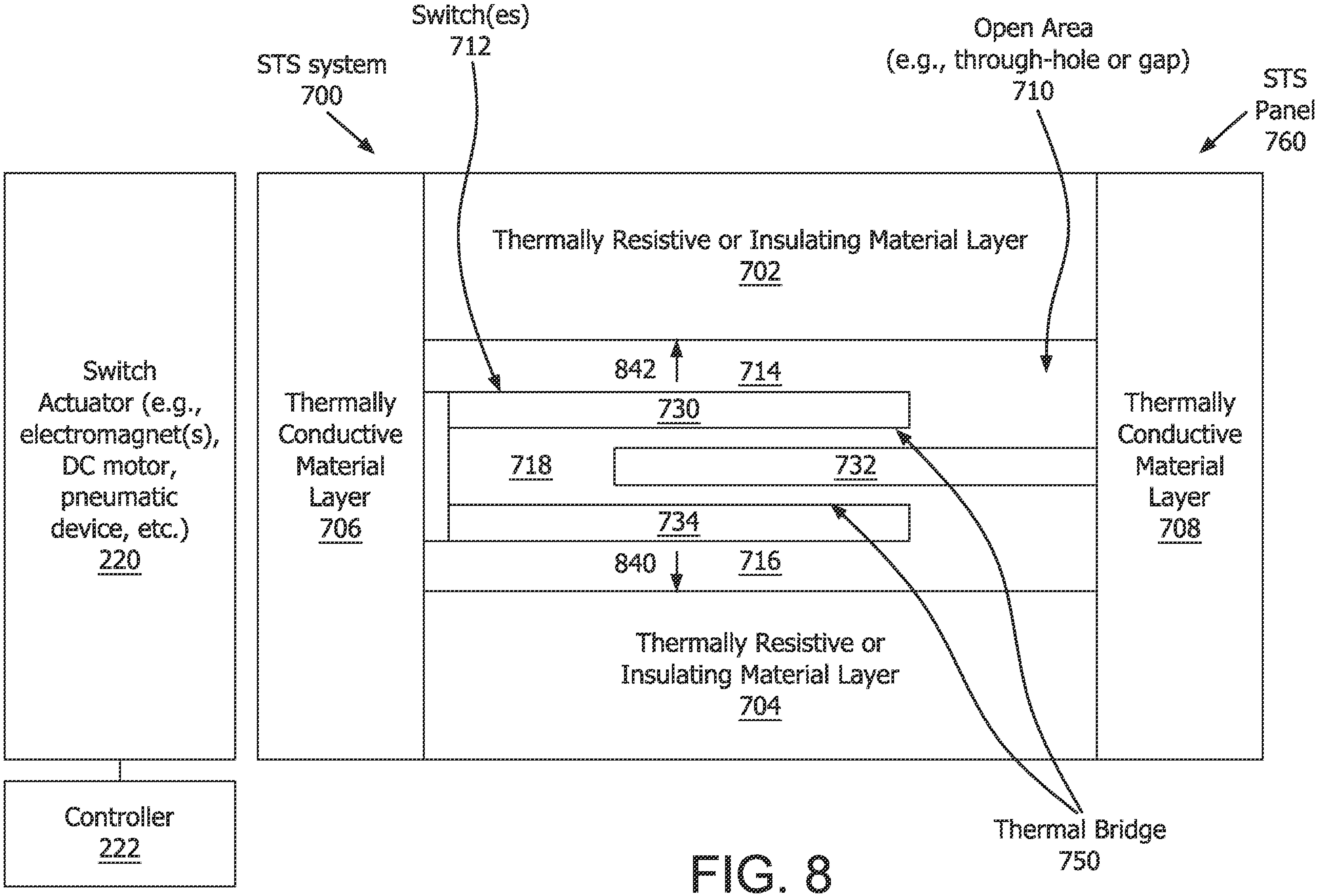


FIG. 8
(OFF or High-R state)

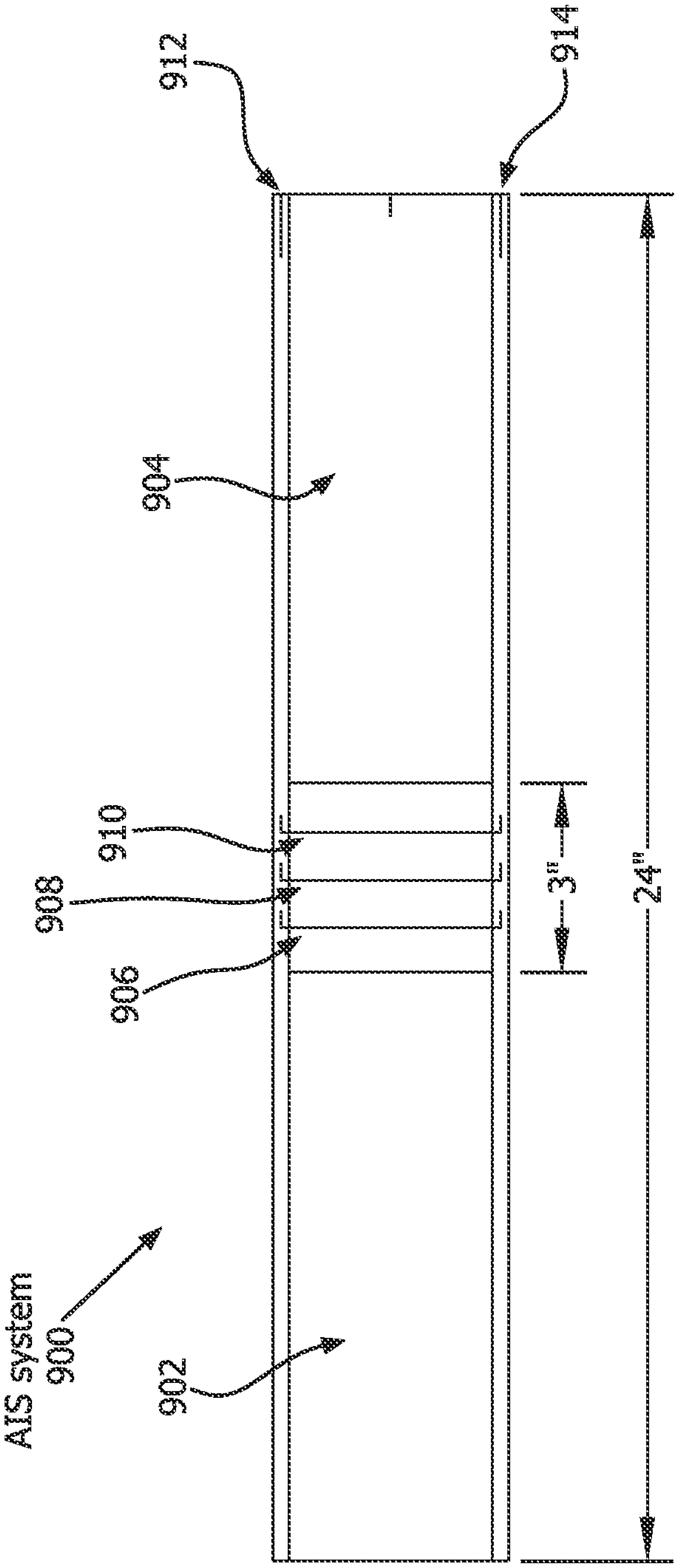


FIG. 9

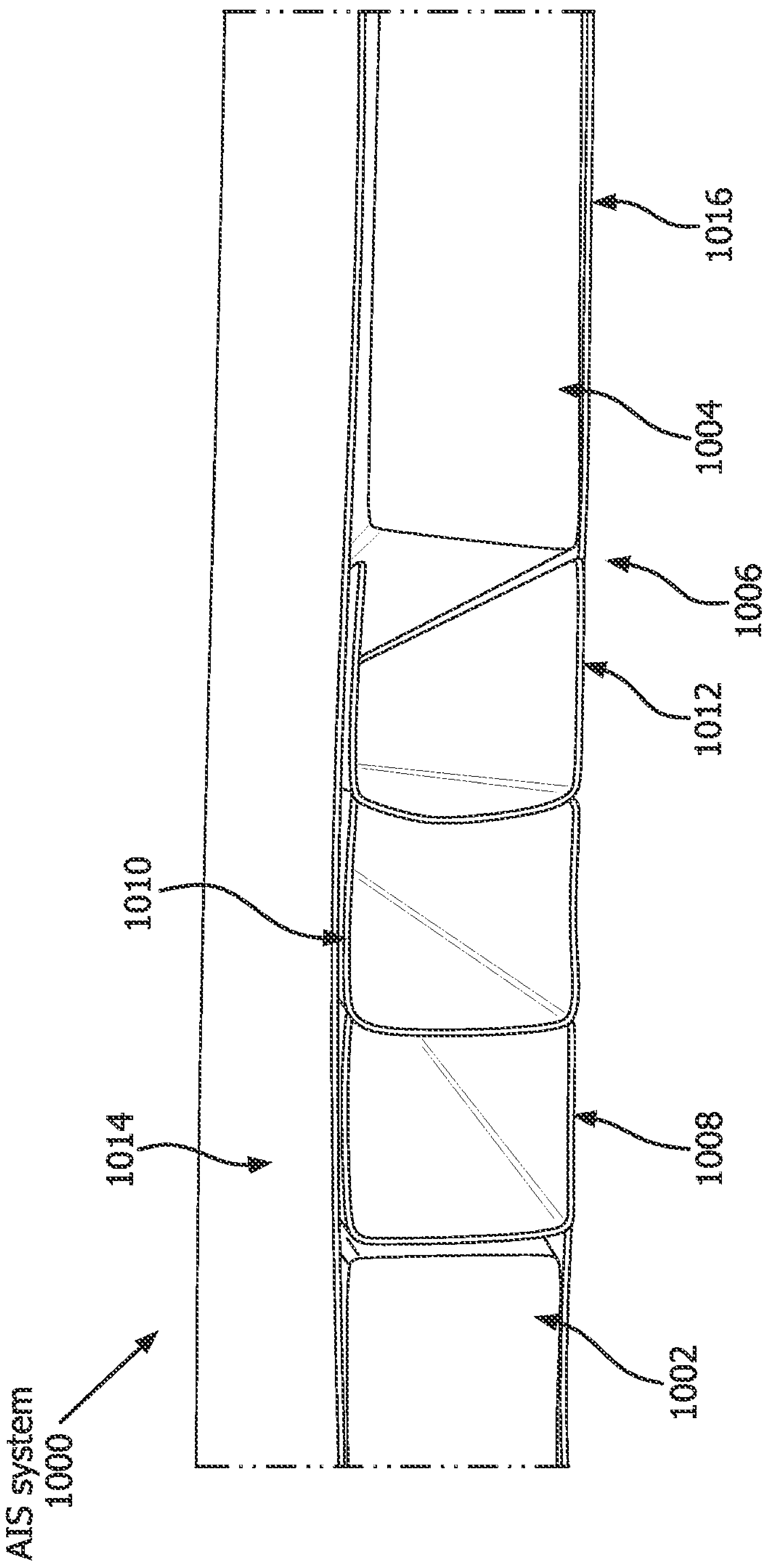


FIG. 10

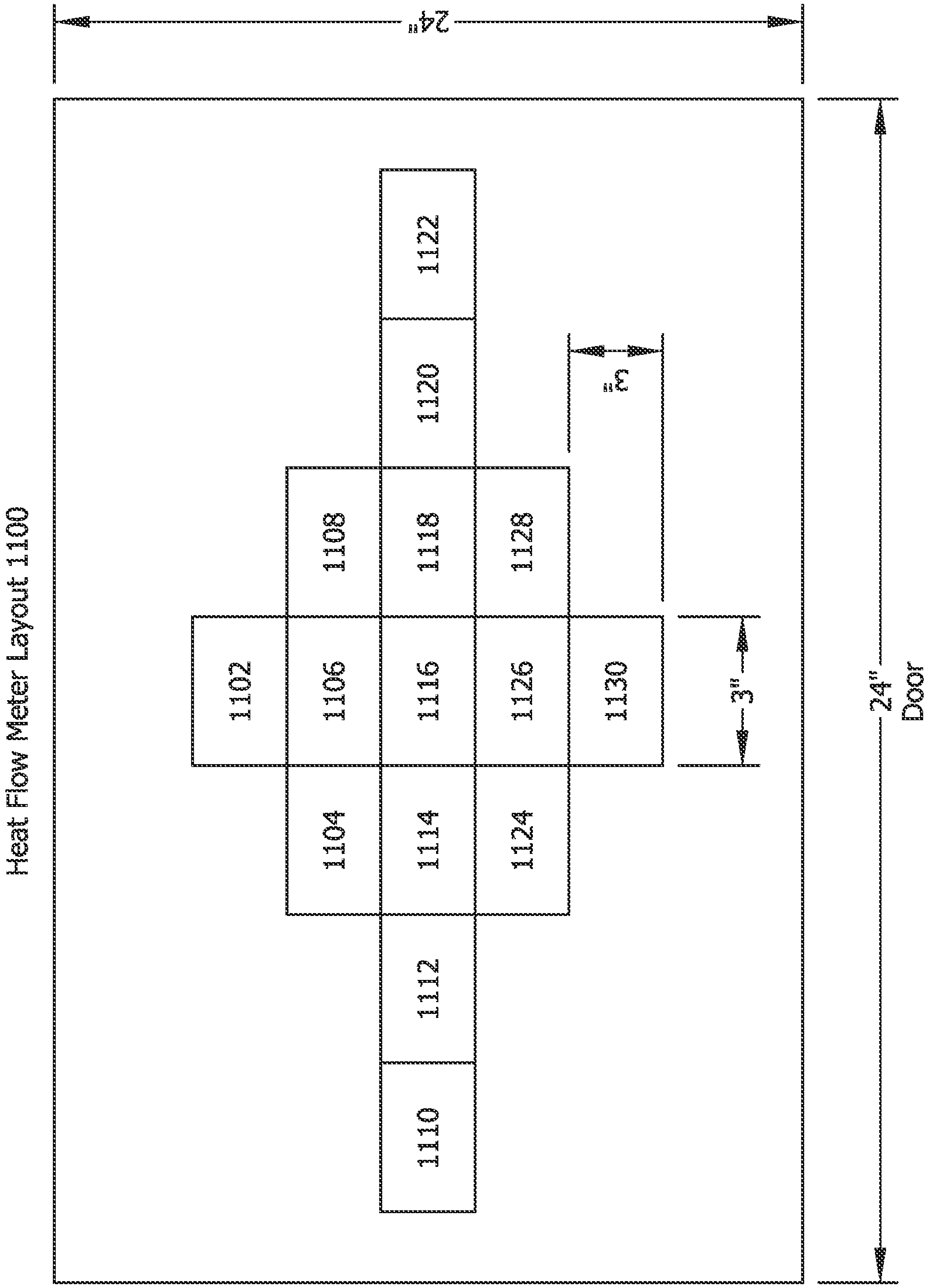

Heat Flow Meter Layout 1100
24"
24"
Door
3"
3"
1102
1104
1106
1108
1110
1112
1114
1116
1118
1120
1122
1124
1126
1128
1130

FIG. 11

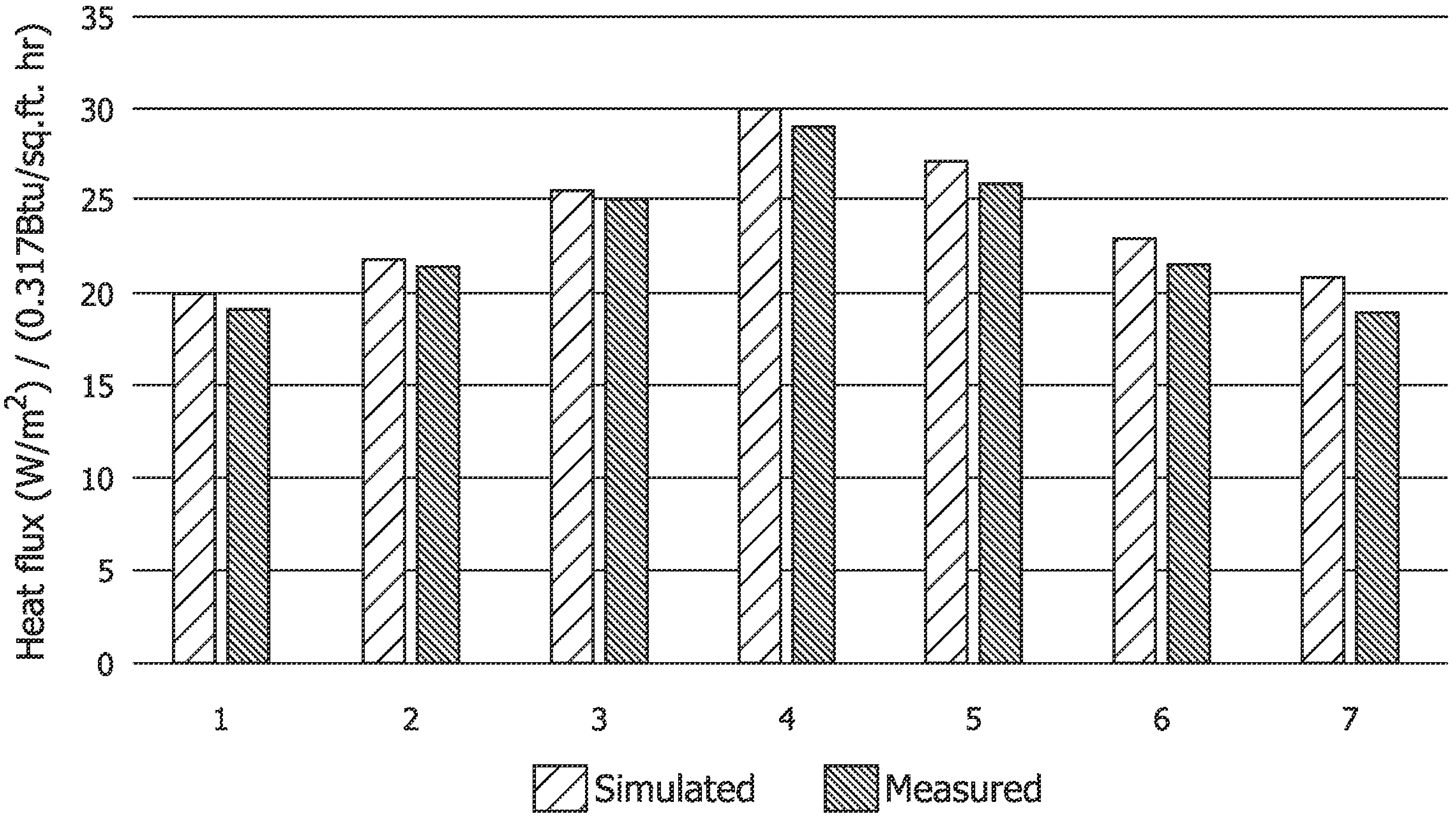

Heat flux (W/m²) / (0.317Btu/sq.ft. hr)
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
Simulated
Measured

FIG. 12

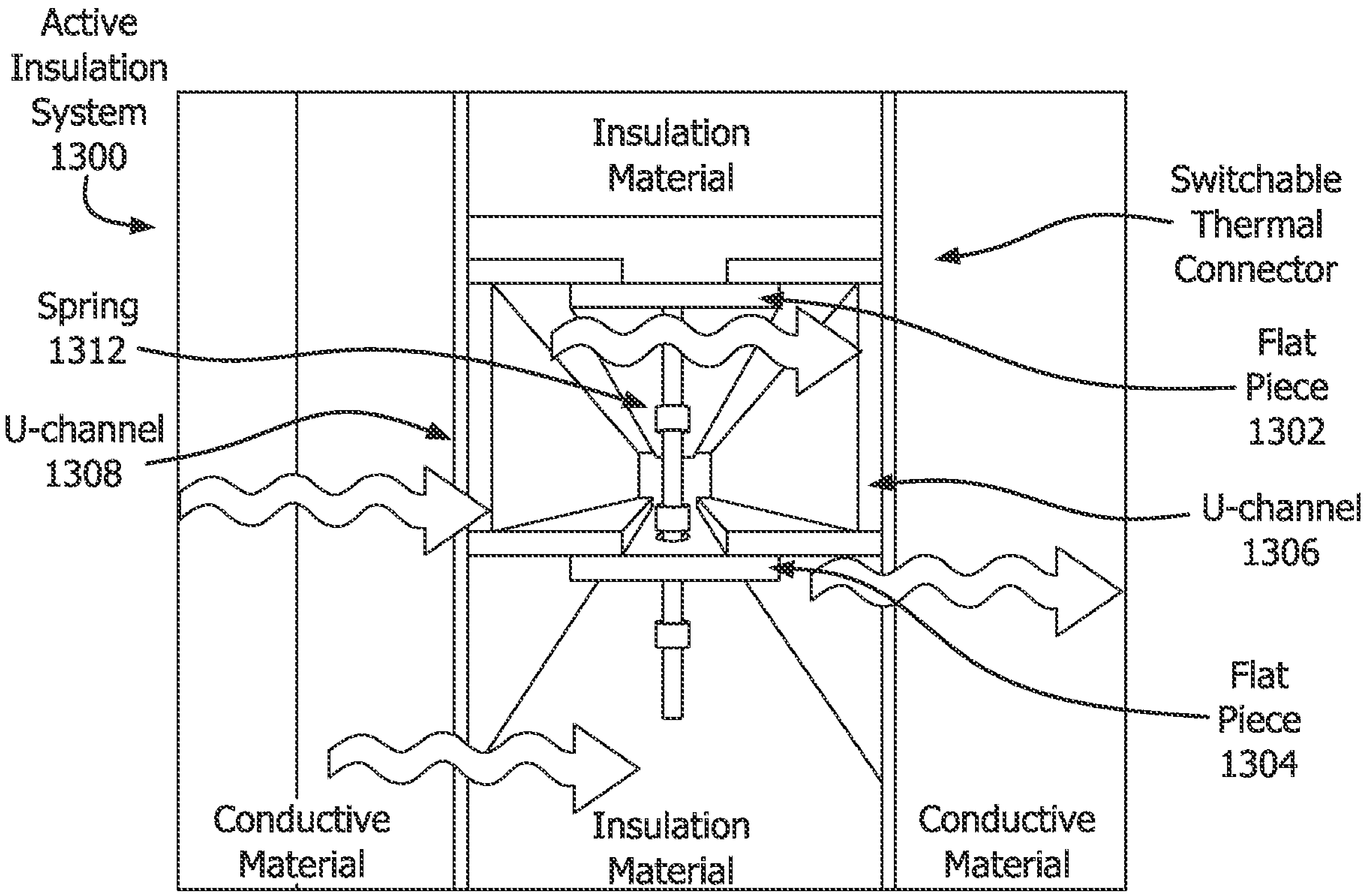


FIG. 13A

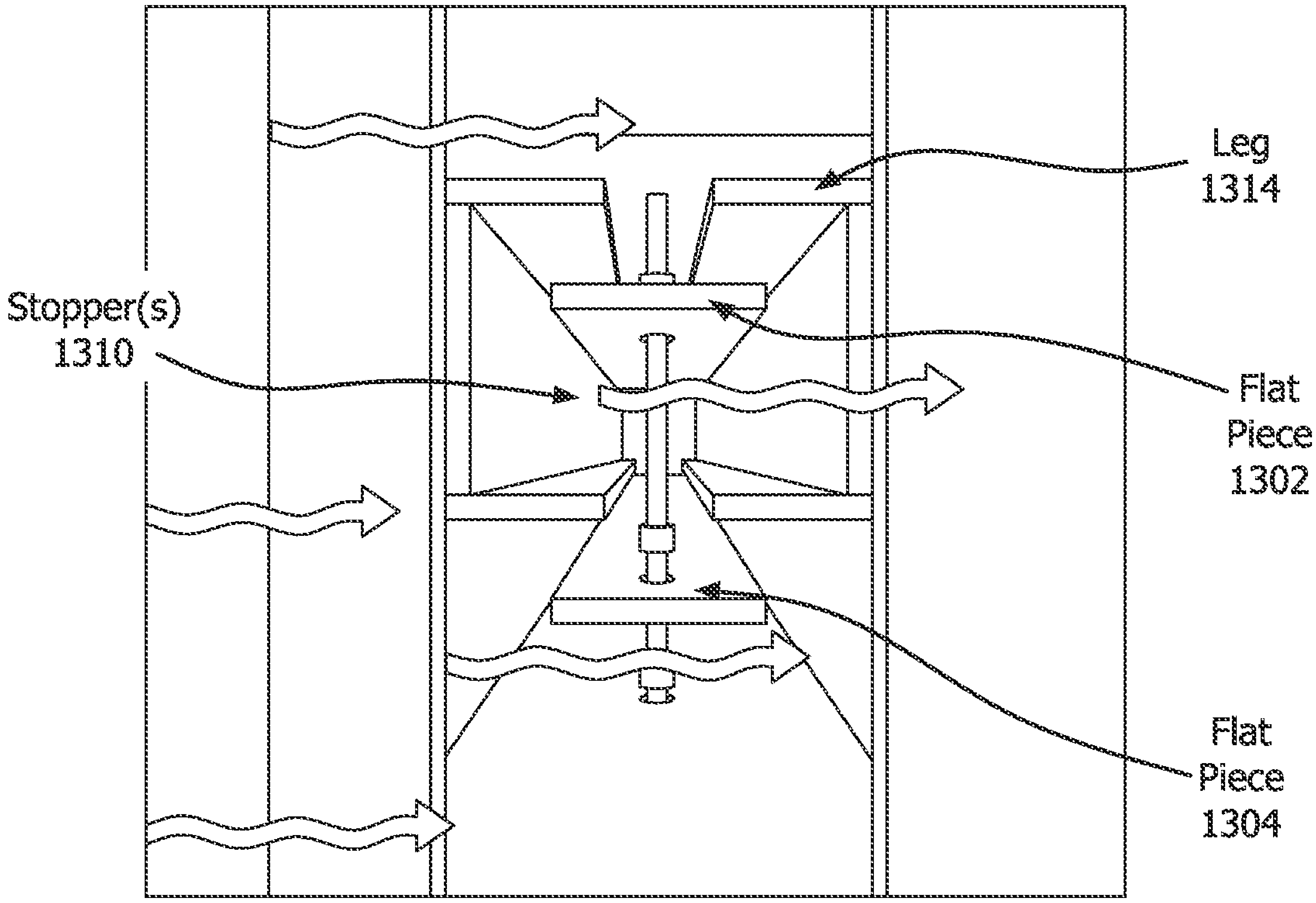


FIG. 13B

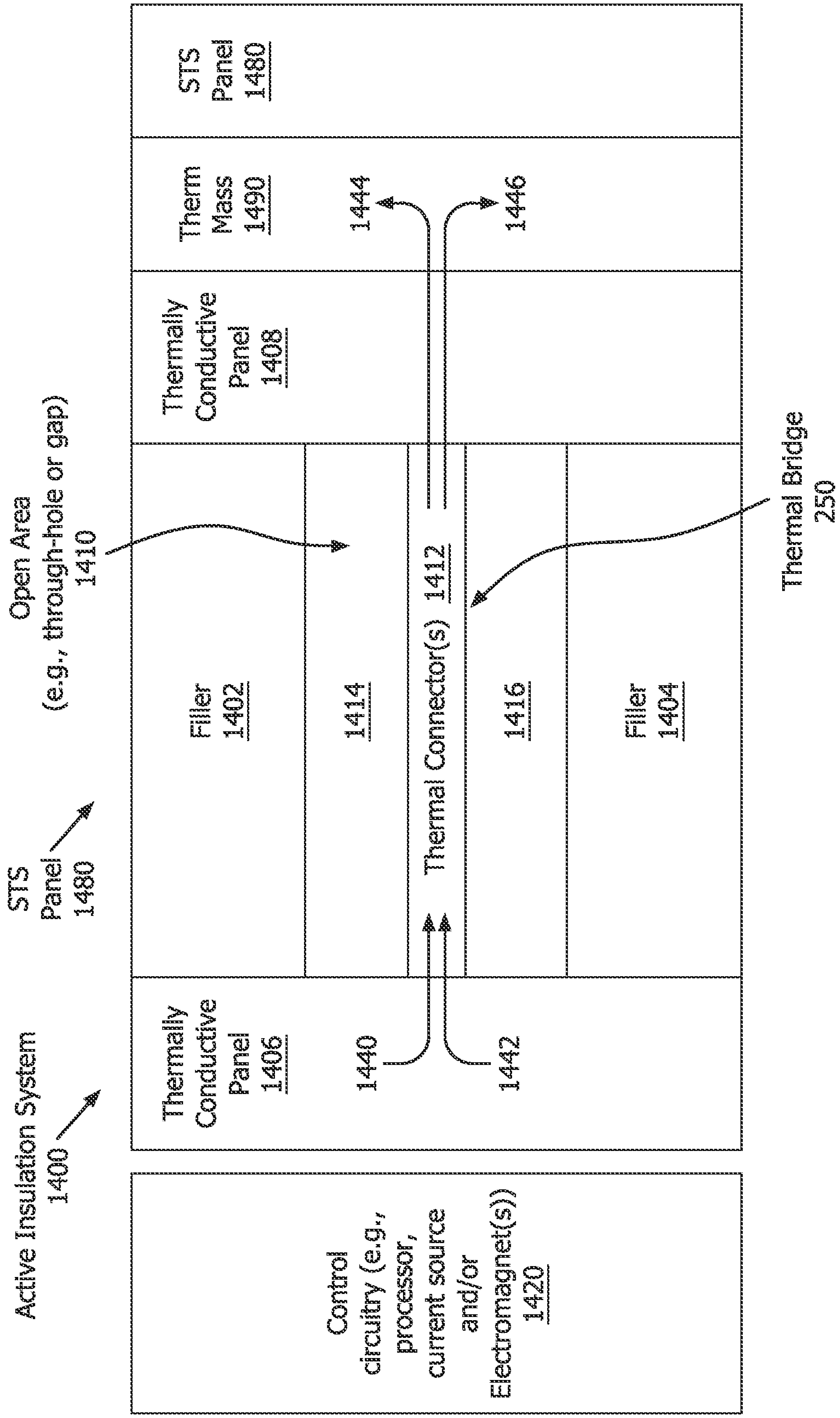


FIG. 14
(ON or Low-R state)

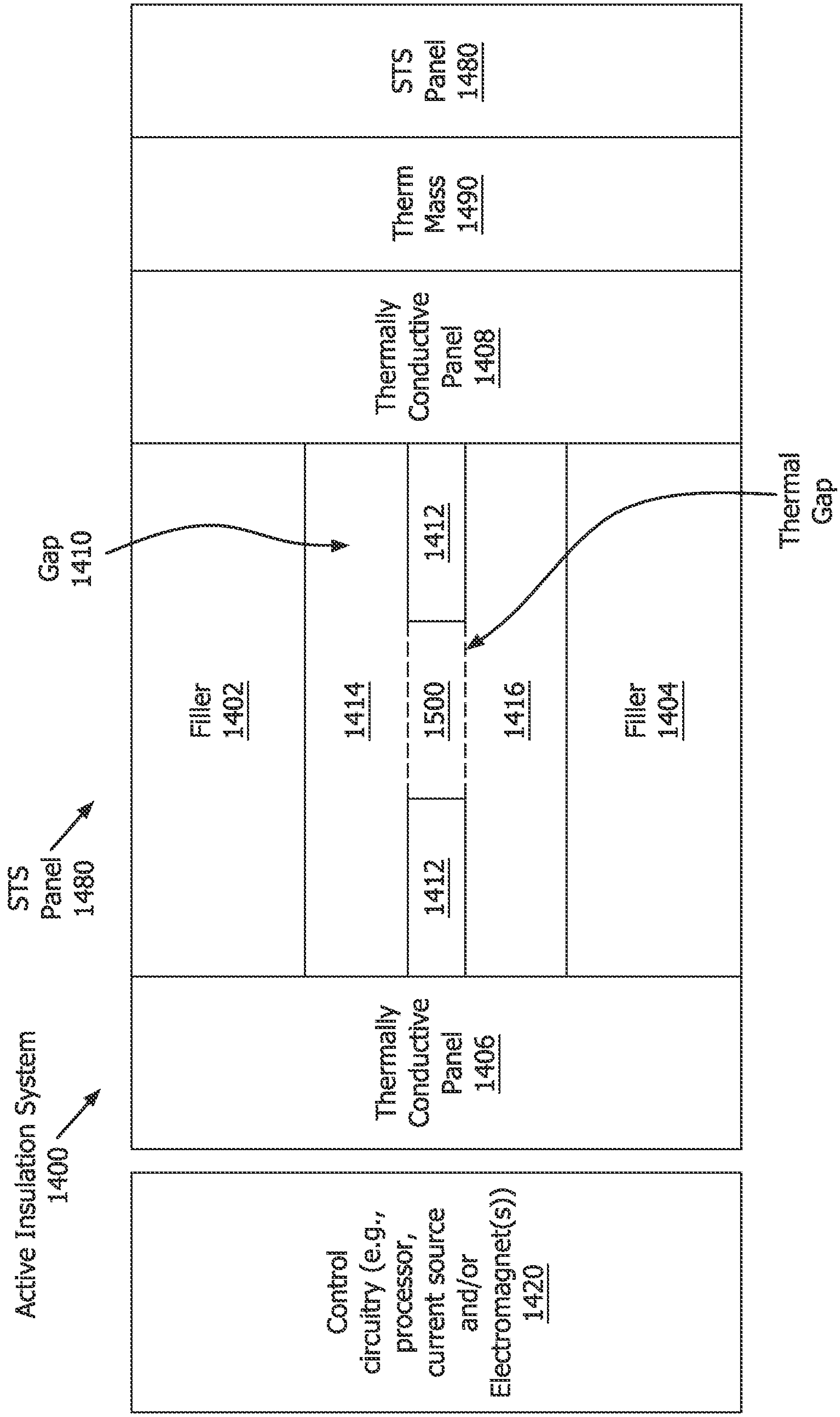


FIG. 15
(OFF or High-R state)

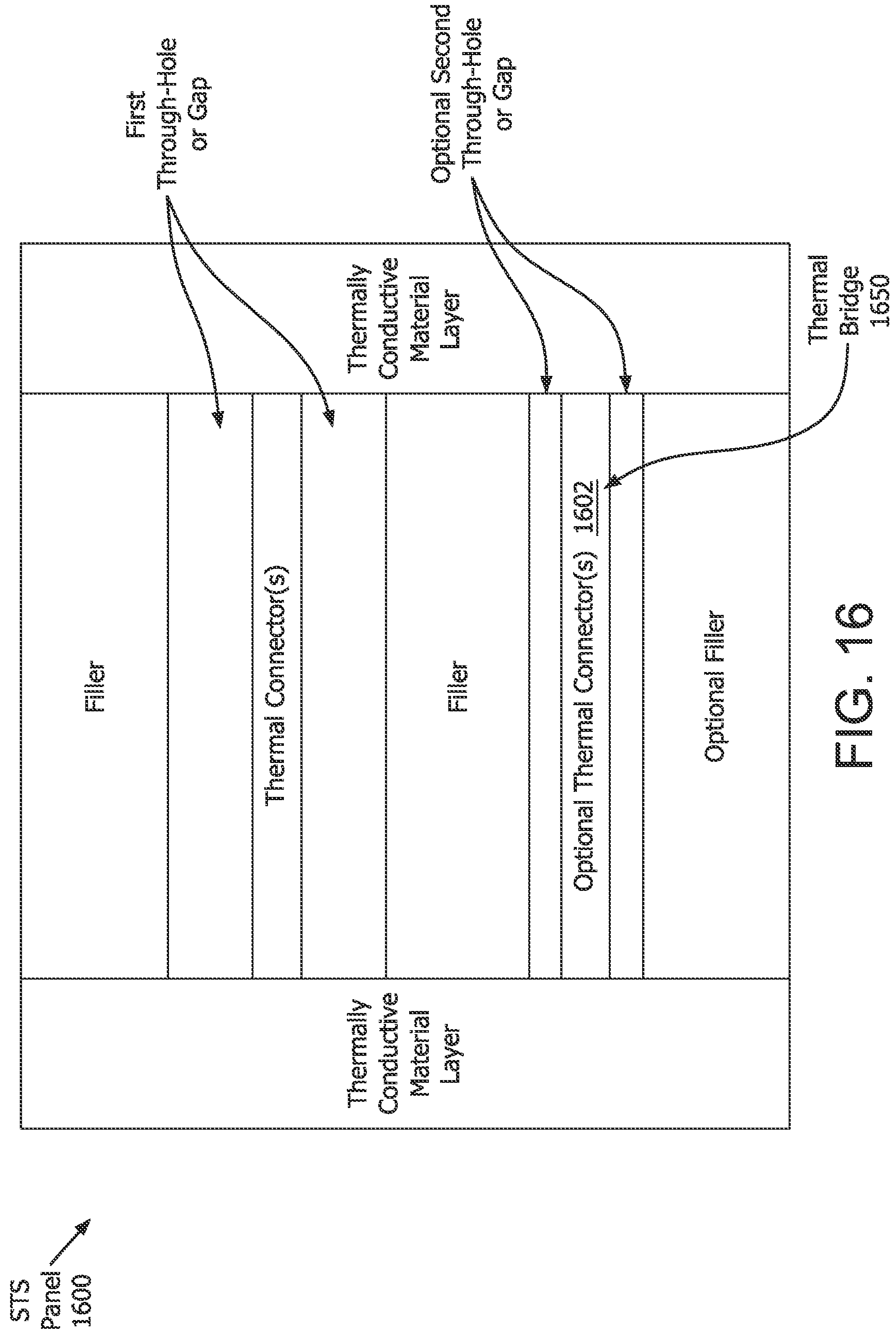

STS Panel 1600
First Through-Hole or Gap
Optional Second Through-Hole or Gap
Thermally Conductive Material Layer
Filler
Thermal Connector(s)
Filler
Optional Thermal Connector(s) 1602
Optional Filler
Thermally Conductive Material Layer
Thermal Bridge 1650

FIG. 16

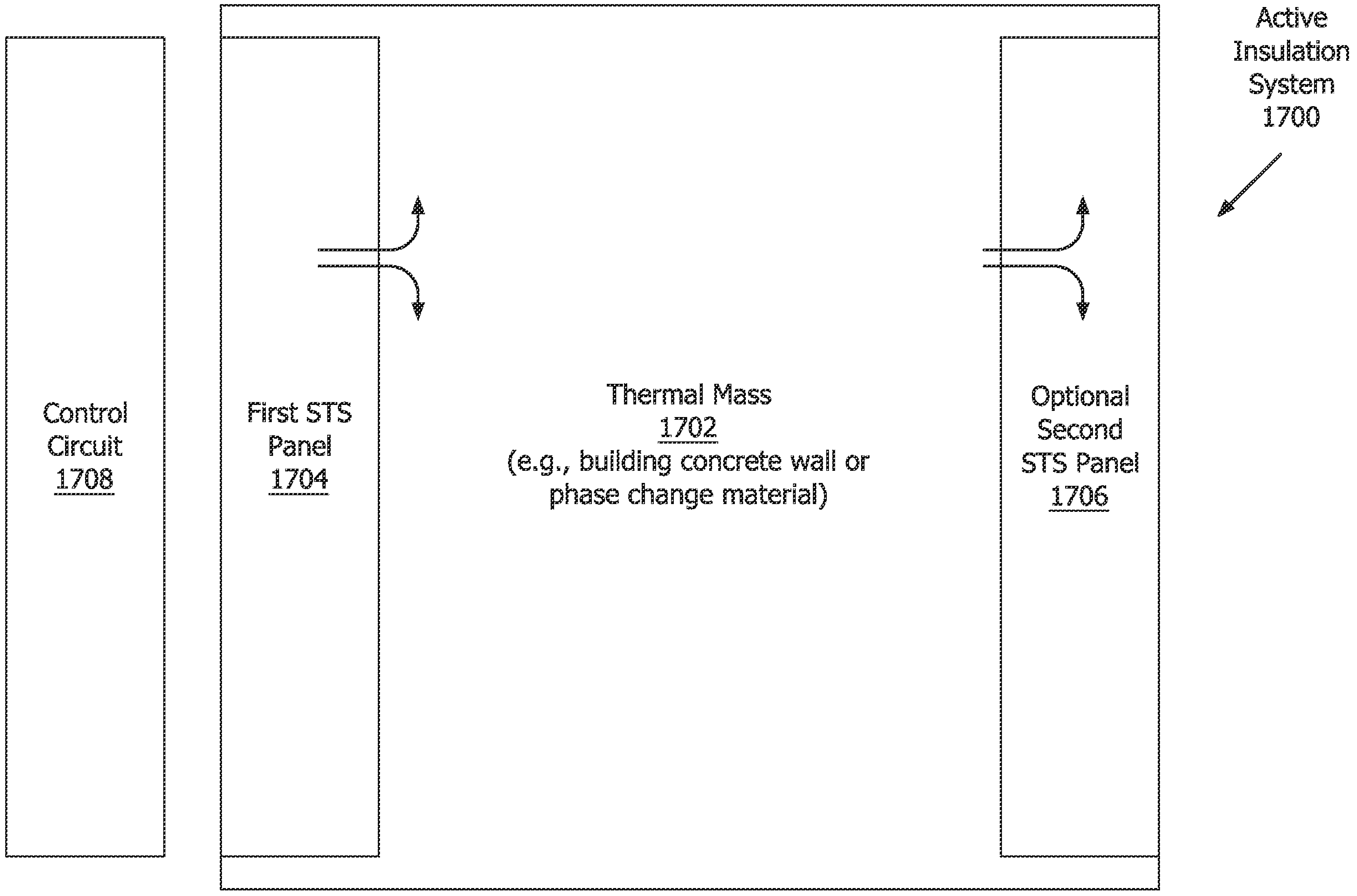

Active Insulation System 1700
Control Circuit 1708
First STS Panel 1704
Thermal Mass 1702 (e.g., building concrete wall or phase change material)
Optional Second STS Panel 1706

FIG. 17

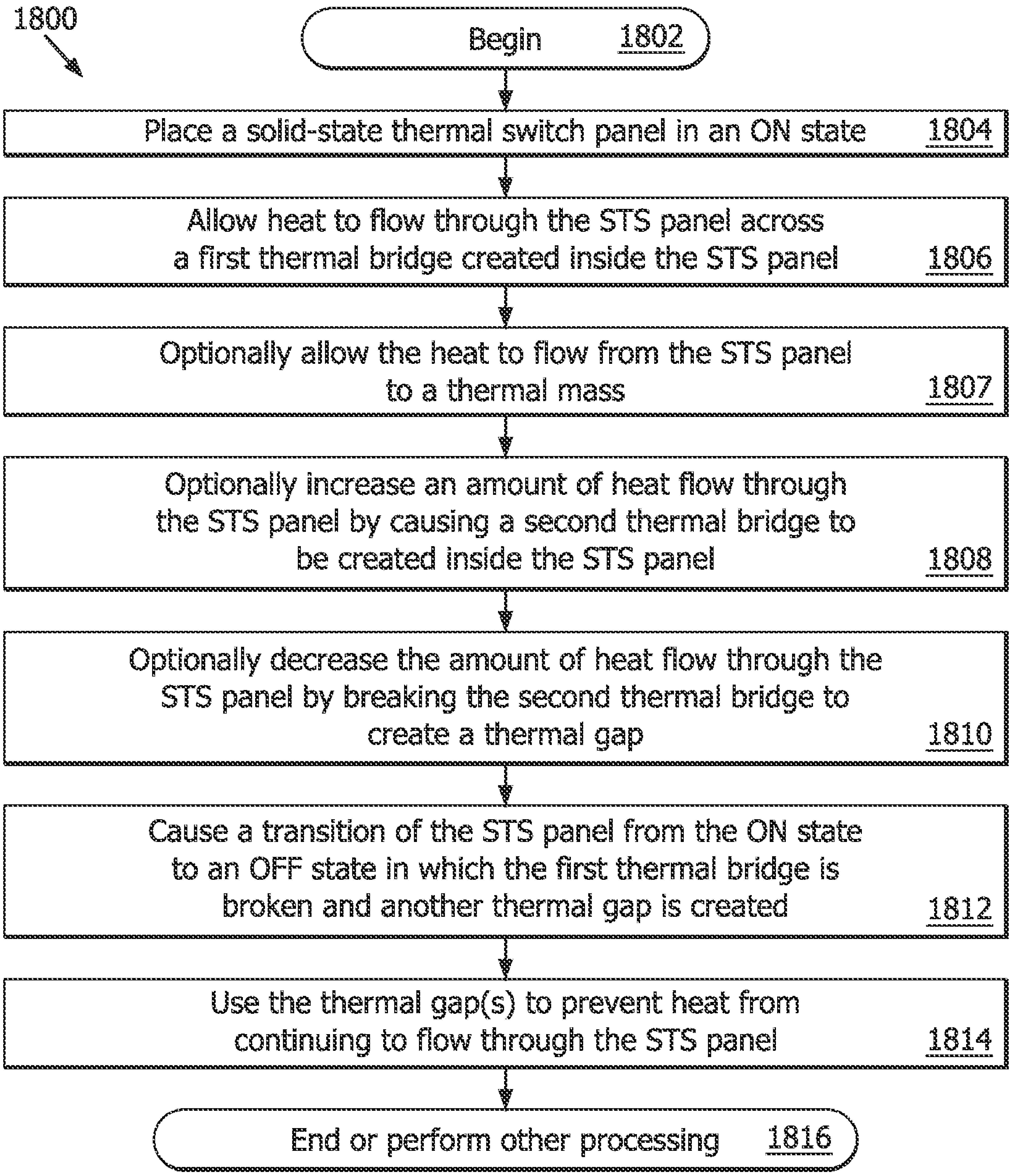

1800
Begin 1802
Place a solid-state thermal switch panel in an ON state 1804
Allow heat to flow through the STS panel across a first thermal bridge created inside the STS panel 1806
Optionally allow the heat to flow from the STS panel to a thermal mass 1807
Optionally increase an amount of heat flow through the STS panel by causing a second thermal bridge to be created inside the STS panel 1808
Optionally decrease the amount of heat flow through the STS panel by breaking the second thermal bridge to create a thermal gap 1810
Cause a transition of the STS panel from the ON state to an OFF state in which the first thermal bridge is broken and another thermal gap is created 1812
Use the thermal gap(s) to prevent heat from continuing to flow through the STS panel 1814
End or perform other processing 1816

FIG. 18

SOLID-STATE THERMAL SWITCH PANEL FOR THERMAL STORAGE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application 63/429,238 filed Dec. 1, 2022, entitled “Solid-State Thermal Switch Panel for Thermal Storage”, the entire disclosure of which incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

[0002] This invention was made with government support under Contract No. DE-AC05-00OR22725 awarded by the U.S. Department of Energy. The government has certain rights in this invention.

FIELD OF THE INVENTION

[0003] The present document relates to electronic circuits. More particularly, the present document concerns solid-state thermal switch systems.

BACKGROUND

[0004] Building envelopes are typically passive systems that do not allow controlling charging and discharging of thermal energy stored in materials with large thermal mass (e.g., concrete or phase change materials (PCM)) when conditions are favorable. Simulations have shown that thermal mass enclosed between tunable R-value materials (similar to the one illustrated in FIG. **1**) in the walls of a house could reduce annual heating, ventilation and air conditioning (HVAC) energy use by up to 70% and shed or shift peak demand and shape HVAC loads.

[0005] Conventional active insulation systems can have a tunable thermal conductivity. However, the conventional active insulation systems utilize changes in gas pressure, liquid or air convection, multi-layer structures, or thermal diodes, which can have slow switch speed, small ON/OFF ratio, leak concerns, large energy consumption to switch and maintain a state, fragility, and high cost. As a result, none of the conventional active insulation systems has achieved success in practical applications or commercialization.

SUMMARY

[0006] The present document concerns a solid-state thermal switch (STS) panel. The STS panel comprises: a filler formed of a first thermally resistive or insulating material and having a first open area; first and second layers of thermally conductive material that are spaced apart from each other, extend parallel to each other, and sandwich the filler such that the first open area extends from the first layer of thermally conductive material to the second layer of thermally conductive material; and a first thermal connector disposed in the first open area (a) so as to reside between and be spaced apart from the filler, and (b) so as to reside between and be in contact with the first and second layers of thermally conductive material. The first thermal connector is switchable between a first position in which a thermal bridge is created thereby to allow heat transfer between the first and second layers of thermally conductive material, and a second position in which the thermal bridge is broken and a thermal gap is created by the first thermal connector to prevent said heat transfer between the first and second layers of thermally conductive material. The first thermal connector may be switchable between the first and second positions by tilting, rotating or translational movement.

[0007] The first thermal connector may include, but is not limited to, a ferromagnetic material, a diamagnetic material or a paramagnetic material configured to facilitate switching of the first thermal connector using at least one electromagnet. The first thermal connector comprises: a first portion having a first end suspended in the open area of the filler and a second end connected to the first layer of thermally conductive material; and a second portion having a third end suspended in the open area of the filler and a fourth end connected to the second layer of thermally conductive material. The first thermal connector is switchable between the first and second positions by tilting or rotating of the first end of the first portion thereof that is suspended in the open area. Alternatively, the first thermal connector is switchable between the first and second positions by translational movement of the first portion thereof towards and away from a second portion thereof.

[0008] The STS panel may also comprise a second thermal connector disposed in the first open area that is switchable between two positions independent from any switching of the first thermal connector between the first and second positions. A second open area is provided with the filler. Another thermal connector is disposed in the second open area so as to reside between and be spaced apart from the filler, and so as to reside between and be in contact with the first and second layers of thermally conductive material. Switching of the another thermal connector is controllable independent from any switching of the first thermal connector.

[0009] The filler may comprise a second thermally resistive or insulating material. In this case, the first open area may comprise a gap between the first and second thermally resistive or insulating materials.

[0010] The present document also concerns an active insulation system. The active insulation system comprises: a thermal mass (e.g., concrete, a phase change material or container filled with a fluid such as water); an STS panel positioned internal to the thermal mass or adjacent and in contact with the thermal mass; and a control circuit configured to control switching of the first thermal connector between first and second positions. The control circuit may be external to the first STS panel or at least partially disposed internal to the first STS panel.

[0011] The STS panel comprises: a filler formed of a first thermally resistive or insulating material and having a first open area; first and second layers of thermally conductive material that are spaced apart from each other, extend parallel to each other, and sandwich the filler such that the first open area extends from the first layer of thermally conductive material to the second layer of thermally conductive material; and a first thermal connector disposed in the first open area (a) so as to reside between and be spaced apart from the filler, and (b) so as to reside between and be in contact with the first and second layers of thermally conductive material. The first thermal connector is switchable between the first position in which a thermal bridge is created thereby to allow heat transfer between the first and second layers of thermally conductive material, and the second position in which the thermal bridge is broken and a thermal gap is created by the first thermal connector to prevent said heat transfer between the first and second layers of thermally conductive material.

[0012] The active insulation system may also comprise a second solid-state thermal switch panel that is positioned such that the thermal mass is sandwiched between the first and second solid-state thermal switch panels. The first thermal connector of the first STS panel is switchable independent from any switching of a second thermal connector of the second STS panel.

[0013] This document also concerns a method for operating an STS panel. The method comprises: placing the solid-state thermal switch panel in an ON state in which a first thermal bridge is provided, by a first thermal connector, between a first thermally conductive material and a second thermally conductive material spaced apart from the first thermally conductive material via a filler formed of a first thermally resistive or insulating material; allowing heat to flow from the first thermally conductive material across the first thermal bridge to the second thermally conductive material; causing movement by at least a portion of the first thermal connector to transition the solid-state thermal switch panel from the ON state to an OFF state in which the first thermal bridge is no longer being provided by the first thermal connector; and using a first thermal gap created by the first thermal connector to prevent the heat from continuing to flow from the first thermally conductive material to the second thermally conductive material when the solid-state thermal switch panel is in the OFF state. The movement of the at least a portion of the thermal connector comprises by tilting, rotating or translational movement in an open area of the filler.

[0014] The method may also comprise: increasing an amount of heat flow from the first thermally conductive material to the second thermally conductive material by causing a second thermal connector to provide a second thermal bridge therebetween; and decreasing the amount of heat flow from the first thermally conductive material to the second thermally conductive material by causing the second thermal connector to break the second thermal bridge and create a second thermal gap, while the first thermal bridge is still being provided by the first thermal connector.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The present solution will be described with reference to the following drawing figures, in which like numerals represent like items throughout the figures.

[0016] FIG. **1** provides an illustration showing a scalable solid-state thermal switch (STS) coupled with a thermal mass of a wall.

[0017] FIGS. **2-3** provide illustrations of an STS system **200** in an ON (or LOW-R) state and an OFF (or High-R) state.

[0018] FIG. **4** provides an illustration showing COMSOL simulation results in a left-most graph and zoomed-in views of a material layout of the STS system of FIG. **2** in the right graphic. The ON (upper right graphic) and OFF (lower right graphic) states give R-values of R-1/in and R-12/in, respectively.

[0019] FIGS. **5-6** provide illustrations of another STS system in its ON (or Low-R) state and its OFF (or High-R) state.

[0020] FIGS. **7-8** provide illustrations of another STS system in its ON (or Low-R) state and its OFF (or High-R) state.

[0021] FIG. **9** provides an illustration of an active insulation system (AIS).

[0022] FIG. **10** provides an illustration of another AIS.

[0023] FIG. **11** provides an illustration showing a heat flow meter layout.

[0024] FIG. **12** provides a graph showing a heat flux measurement and simulation values from an AIS prototype at heat flux locations at 3" increments.

[0025] FIGS. **13**A-**13**B (collectively referred to herein as "FIG. **13**") provide illustrations showing (A) the R-low state in which flat pieces are engaged with U-channel and (B) the R-high state in which there is not contact between the flat pieces and the U-channels.

[0026] FIGS. **14-15** provide illustrations of an active insulation system in an ON (or LOW-R) state and an OFF (or High-R) state.

[0027] FIG. **16** provides an illustration of another STS system.

[0028] FIG. **17** provides an illustration of another active insulation system.

[0029] FIG. **18** provides a flow diagram of an illustrative method for operating an STS panel.

DETAILED DESCRIPTION

[0030] The present solution concerns an STS system that can change the effective R-value of a thermal barrier of a building envelope between Low-R (e.g., ≤1) and High-R (e.g., ≥10) to provide a large effective thermal conductivity switching ratio (e.g., ≥10) instantaneously and on-demand. The STS system uses a small amount of energy to switch between a Low-R state and a High-R state, where energy is not required to retain a state. The STS system can be integrated with a thermal mass in building envelopes to charge and discharge the thermal mass when environmental conditions are favorable. The STS system can use the stored heat or coolness to shed, shift or shape HVAC loads as needed.

[0031] The STS system comprises an active insulation system that can satisfy the following features: 1) has a large switching ratio of 5-10×; 2) has low thermal conductance at OFF state; 3) has high thermal conductance at ON state; 4) needs low energy input for switching; 5) uses a building-compatible switching mechanism; and 6) uses reliable contacts for mechanical switches. The STS system is scalable, cost-effective, fast, and robust. The STS system can achieve Low-R (≤1) and High-R (≥10).

[0032] FIGS. **2-3** provide illustrations of an STS system **200** in an ON (or LOW-R) state and an OFF (or High-R) state. The STS system **200** comprises at least one STS panel **260** and a control circuit **220**, **222**. STS panel **260** comprises a filler **280** sandwiched between two layers of thermally conductive materials **206**, **208**. The filler **280** can include one or more layers **202**, **204** of thermally resistive or insulating material. The thermally resistive or insulating material(s) can include any material(s) selected in accordance with a particular application. The same or different material can be used for the thermally resistive or insulating material layers. For example, both layers **202** and **204** of the thermally resistive or insulating material are selected to comprise vacuum insulation panels (VIPs). The present solution is not limited to the particulars of this example.

[0033] The filler **280** can have one or more open areas (e.g., through-holes or gaps) **210** that extend in a direction **282** between the thermally conductive materials **206**, **208**. The size **210** of each open area can be selected in accordance with any given application. In some scenarios, the open area **210** is designed to have a minimal overall size.

[0034] Switchable thermal connector(s) **212** is(are) disposed in the open area **210**. The switchable thermal connectors can include, but are not limited to, thermal switch (es) that is(are) made of a paramagnetic material, a diamagnetic or a ferromagnetic material with a high thermal conductivity k. The paramagnetic material can include, but is not limited to, aluminum. The diamagnetic material can include, but is not limited to, copper. The ferromagnetic material can include, but is not limited to, steel. Portions **214**, **216** of open area **210** comprise air. The air facilitates movement (e.g., retraction or rotation) of the switchable thermal connector(s) **212**.

[0035] At the ON (or Low-R) state shown in FIG. **2**, the switchable thermal connector(s) **212** create(s) a thermal bridge **250** that connects the two layers of thermally conductive materials **206**, **208** to each other. This connection enhances the heat flow through the STS panel **260** as shown by arrows **240**, **242**, **244**, **246**.

[0036] At the OFF (or High-R) state shown in FIG. **3**, the switchable thermal connector(s) **212** will move (e.g., retract or rotate) so that an additional area **300** is created in the open area **210** that fills with air. This additional area **300** is referred to herein as a thermal gap. In effect, the two layers of thermally conductive materials **206**, **208** are disconnected from each other via the switchable thermal connector(s) **212**. In effect, heat minimally flows from thermally conductive material **206** to thermally conductive material **208** through thermal connector(s) **212**.

[0037] Switching the STS system **200** between the ON and OFF states is achieved using an actuator **220** which is controlled by controller **222**. The actuator **220** can include, but is not limited to, electromagnet(s), a DC motor, and/or pneumatic device. The electromagnet(s) can include, but is(are) not limited to, low voltage electromagnet(s) such as 6 to 12 VDC electromagnet(s). The electromagnet(s) can be selectively supplied current from the controller **222** based on certain criteria. For example, the controller **222** can detect when a temperature of an area **270** on a first side of the STS panel (e.g., inside a building) exceeds a given value (e.g., 76° F.) and/or is less than a temperature on a second side of the STS panel (e.g., outside a building or room of a building), and supply current to the switch actuator upon such detection. When current is supplied thereto, the electromagnet(s) cause(s) the thermal connector(s) **212** to move for transitioning the system **200** from the ON (or Low-R) state to the OFF (or High-R) state. Once the system state has been transitioned, the supply of current is discontinued. Notably, the system **200** remains in its OFF (or High-R) state at this time. The continued supply of current to the actuator **220** is not needed to maintain the Off (or High-R) state. System **200** may be transitioned back to its ON (or Low-R) by once again supplying current to the actuator **220**.

[0038] In the multiple thermal connector scenario, one or more thermal connectors **212** can disposed in the single open area **210**. Additionally or alternatively, thermal connectors can be disposed in respective open areas in filler **280** as shown in FIG. **16**. The thermal connections can be triggered individually to have some thermal connectors ON and some thermal connectors OFF to achieve an R-value between High-R and Low-R. The STS system **200** remains in the ON or OFF state even after the electromagnet(s) **222** is(are) de-energized until it is reenergized to change the state of the STS system **200**. Thus, energy is not needed to maintain the ON state or the OFF state of the STS system **200**.

[0039] FIG. **4** shows simulation results of an STS system that is the same as or similar to STS system **200**. The ON (or Low-R) state gives an R-value of R-1/in, while the OFF (High-R) state gives an R-value of R-12/in.

[0040] FIGS. **5**-**6** provide illustrations of another STS system **500** in its ON (or Low-R) state and its OFF (or High-R) state. STS system **500** is similar to STS system **200** except for the switchable thermal connector(s) **512**. Thermal connector(s) **512** is(are) configured to move (e.g., retract or flip) for selectively transitioning the STS system **500** between its ON (or Low-R) state shown in FIG. **5** and its OFF (or High-R) state shown in FIG. **6**. In the ON (or Low-R) state, portions **514**, **516** of open area (e.g., through-hole or gap) **510** comprise air and the thermal connector(s) **512** create a closed connection condition in which a thermal bridge **550** is provided between thermally conductive materials **506** and **508**. Heat can flow from thermally conductive material **506** to thermally conductive material **508** through thermal bridge **550** as shown by arrows **540**, **542**, **544**, **546**.

[0041] In the OFF (or High-R) state, the thermal connectors(es) **512** create an open connection condition in which the thermally conductive materials **506** and **508** are disconnected from each other. An additional open area **600** in open area **510** is created that fills with air. This additional area **600** is referred to herein as a thermal gap. Area **600** has a different overall shape as compared to the shape of area **300** of FIG. **3**. As a result of creation of the thermal gap, heat no longer flows from thermal conductive material **506** to thermal conductive material **508** through thermal bridge **550**.

[0042] FIGS. **7**-**8** provide illustrations of another STS system **700** in its ON (or Low-R) state and its OFF (or High-R) state. STS system **700** is similar to STS system **200** except for the thermal connector(s) **712**. Thermal connector (s) **712** is(are) configured to retract for selectively transitioning the STS system **700** between its ON (or Low-R) state shown in FIG. **7** and its OFF (or High-R) state shown in FIG. **8**. In the ON (or Low-R) state, portions **714**, **716**, **718** of open area (e.g., through-hole or gap) **710** comprise air and the thermal connector(s) **712** create a closed connection condition in which a thermal bridge **750** is provided between thermally conductive materials **706** and **708**. The closed connection condition is formed when portions **730**, **734** are in contact with portion **732**. Heat can flow from thermally conductive material **706** to thermally conductive material **708** via thermal bridge **750** as shown by arrows **740**, **742**, **744**, **746**.

[0043] In the OFF (or High-R) state, the thermal connector (s) **712** create an open connection condition to disconnect the thermally conductive materials **706** and **708** to each other. Portions **714**, **716** of open area **710** have been made smaller, while area **718** in open area **710** has been made larger. Portions **730**, **734** have moved in respective directions **840**, **842** away from portion **732**. As such, a thermal gap **850** has been formed between thermally conductive materials **706** and **708**. In effect, the heat no longer flows from thermally conductive material **706** to thermally conductive material **708** via thermal connector(s) **712**.

[0044] An STS system according to the present solution has been evaluated using a design that consists of 10 mil-thick aluminum foils for the high thermal conductivity materials and 1-inch thick VIPs for the thermally resistive or insulating materials. The ratio of the thermal connector to the insulation area is 1:100, which means that the number of thermal connectors was not large. The thermal conductivity of the thermal connector material was 20 W/mK, which is a reasonable value considering the potential contact resistance in the thermal connector. Preliminary finite element (FE) heat transfer analysis of the proposed system showed Low-R ~1/inch and High-R ~12/inch.

[0045] The design of the STS system was optimized using FE analysis. A prototype of this design was made and evaluated. More specifically, the effective R-values of the STS system was evaluated at ON and OFF states using a 2 ft×2 ft heat flow meter. Performance of the STS system was optimized by geometry design (such as switch spacing and thickness, mechanical contact area and force, and conducting layer thickness) iteratively to achieve the desired R-values.

[0046] After finalizing the bench-scale design, a large-scale prototype (e.g., 4 ft×4 ft or larger) was made. The large-scale prototype's performance and effective R-values were evaluated at ON and OFF states using a hot box apparatus. To evaluate the system's scalability, durability, and performance in a large-scale application, a study was performed using the STS system coupled with high-thermal mass walls at one of ORNL's natural exposure test facilities for one year.

[0047] Risks were mitigated by: 1) minimizing the contacting thermal resistance for the ON state; 2) minimizing the bridge effect at OFF state; and 3) repairing and performing maintenance. The mitigation plan included: 1) designed a large contacting area and tight contact and coat the contacting surfaces with high thermal contact conductance materials (such as copper); 2) designed an efficient retraction/rotation system to ensure a large gap for the OFF state; and 3) designed robust modular assembly so that components could be easily replaced.

[0048] For instance, an STS system can include a thermal mass sandwiched between an exterior STS panel and an interior STS panel. The STS system can be operated such that, in the cooling season, thermal connectors in the exterior STS panel would be: (i) in their ON states when the exterior surface temperature is lower (e.g., due to low ambient temperature or night sky radiation) than the thermal mass temperature which allows "charging" the thermal mass (e.g., cool down for the cooling season); and (ii) in their OFF states when the exterior surface temperature is higher than the thermal mass temperature to minimize the heat gain by the thermal mass. Thermal connectors in the interior STS would be: (i) in their OFF states when the thermal mass temperature is higher than the indoor temperature; and (ii) in their ON states when the thermal mass temperature is lower than the indoor temperature and the building needs cooling. This will provide cooling without running the HVAC system.

[0049] In the heating season, thermal connectors in the exterior STS panel would be: (i) in their ON states when the exterior surface temperature is higher (e.g., due to solar radiation) than the thermal mass temperature which allows "charging" the thermal mass (e.g., heat up for the heating season); and (ii) OFF when the exterior surface temperature is lower than the thermal mass temperature to minimize the heat loss from the thermal mass. Thermal connectors in the interior STS panel would be in their OFF states when the thermal mass temperature is lower than the indoor temperature, and in their ON states when the thermal mass temperature is higher than the indoor temperature and the building needs heating.

[0050] The present solution can significantly increase the functions of the thermal mass in buildings by optimizing the utilization of the storage capacity to shed, shift and shape HVAC loads on demand. Simulations indicate the potential to reduce annual HVAC energy use by up to 70% and that these could be increased with advanced controls.

[0051] The present solution can be used generally in fields such as energy, utilities and/or Manufacturing. For example, the present solution can be used for designing building envelopes, thermal energy storage, etc.

AIS Implementation

[0052] Conventional building envelopes have passive insulation systems that cannot respond to dynamic changes in the environment. An AIS includes active insulation materials (AIMs) that dynamically vary the thermal conductivity of the insulation system. Several researchers have evaluated the impact of AIS on building thermal and energy performance by using simulation tools. Up to 70% savings in annual heating and cooling energy and significant reductions in peak demand have been predicted for some climates with wall systems employing AIS. However, materials and assembly development have not yet achieved a cost-effective product that achieves the required performance. Herein, a process is described to develop an AIS that can be installed in a test hut for its performance evaluation. Minimum performance criteria of the AIS system are developed based on R_{min}/R_{max} ratio, required time and efficiency to switch states, and cost estimates. Technologies are discussed to meet the requirements, predict the performance via simulations, develop the experimental setup for bench-scale testing, and construct a full-scale wall assembly with its performance monitored when exposed to natural weather conditions. The selected approach uses off-the-shelf products to create an AIS that can switch R-value between ~1 $ft^2 \cdot {}^\circ F \cdot h/BTU$ ($0.18\ m^2 \cdot K/W$) and ~7 $ft^2 \cdot {}^\circ F \cdot h/BTU$ ($1.23\ m^2 \cdot K/W$) and have a switching time of less than one minute between R-high and R-low.

[0053] The U.S. Energy Information Administration's (EIA's) 2022 Energy Outlook shows commercial and residential buildings in the U.S. used more than 20 quadrillions BTU in 2021. This energy consumption is predicted to increase to 13 quads BTU and 10 quads BTU for residential and commercial buildings, respectively, by 2050. In addition, buildings generate about 40% of annual global CO_2 emissions, and 28% of these emissions are due to the operation of buildings. In 2016, HVAC loads contributed to 30% and 38% of the CO_2 emissions in commercial and residential buildings, respectively.

[0054] To decarbonize buildings and enhance energy savings, renewable energy sources (such as solar and wind) are considered viable options. However, harvesting, storing and consuming energy when needed requires 'intelligent' solutions. Active insulation systems can facilitate automated energy storage from renewable sources to a thermal storage unit and the release of the stored energy into the living space to complement or replace the conventional HVAC sources.

[0055] Simulation studies show that AIS integrated walls can contribute significantly toward energy savings. Residential buildings in climate Zone 5 have the potential to reduce cooling energy load by 30%. Residential prototype buildings for eight cities in different climate zones could achieve annual savings that ranged from 4096 KBtu to 8433 KBtu (1192 to 2471 kWh). Residential buildings in the United States' mild climate zones could save up to 45% in heating and cooling energy consumption. Several recent experimental and simulations works show that not only can active insulation systems elevate energy savings, but it can have a significant impact in peak-load energy shaving. To achieve high-performance active insulation systems, some potential advanced solutions to develop effective dynamically varying insulation solutions are recommended.

[0056] Even though, the above studies show the AIS potential of energy savings and peak demand reduction, there are no case-specific AIS selection protocols and the minimum expected performance metrics. An AIS performance specification, selection criteria and prototype are described herein. The performance of the AIS prototype was tested in a heat flow meter (HFM), and the results were used to validate simulation models that in turn were used to extrapolate findings to optimize AIS parameters for performance enhancement.

AIS Parameter Selection Criteria

[0057] Key parameters such as minimum R-value (R-low) and maximum R-value (R-high), response time, amount of energy needed to change the R-value state, ease of assembly and integration into buildings, robustness, longevity, and the construction and running costs were used as selection criteria for the disclosed AIS technologies.

[0058] To assign percentage weight to each AIS performance evaluation criteria, a minimum requirement for functionality, performance and cost expected of the AIS system is set and shown in TABLE 1.

TABLE 1

Minimum Required Property of the AIS Material

Property	Desired
Rmin/Rmax@thickness	Rmin ~1/Rmax >7 @<2 in (Rmin ~0.176 K · m^2/W/ Rmax >1.233 K · m2/W @50.8 mm)
Time to switch states	<5 min
Actuator	Durable, simple
Efficiency of switching	<1 Wh/ft^2 (<10.8 Wh/m^2)
Cost estimate/ft^2	<\$5/ft^2 (<\$53.8/m^2)

[0059] The R-high and R-low values are selected based on achieving 70% of typical rigid insulation during R-high and having conductive insulation of ~R-1 during the R-low state. Any switching time lower than half an hour provides similar performance. Thus, a 5-minute switching time is set as a minimum switching criteria. A small motor power requirement is used to select the efficiency of switching. The minimum cost estimate is selected based on a combined cost of AIS components, actuating mechanisms and cost of power demand.

AIS Using STS

[0060] An STS that uses different ways of connecting and disconnecting metallic or other highly conductive strips can provide varying low and high R-values to a system. The range of R_{min}/R_{max} can be significantly varied and depends on the spacing of the thermal bridges. An AIS system with the STS was selected for a test based on the performance (e.g., R-min to R-high ratio), construction cost, ease of buildability and scalability.

[0061] The disclosed AIS system uses a metal connector design to switch the active insulation between R-high and R-low. Low-emittance connectors disengage from the interior and exterior cover foils to avoid thermal bridging when the insulation is in an R-high state.

[0062] In the R-low state (e.g., conducting stated), the AIS system opens the connectors in a cavity disallowing conduction along the connectors. The connectors can be made of aluminum or similar material that has high thermal conductivity. Additionally, the AIS system has highly conductive aluminum foils on both the exterior and interior sides of the insulation to allow the heat to spread on the surface and enhance the heat transfer rate.

[0063] The disclosed AIS wall system can further include two interior and exterior active insulation assemblies on both sides of a fully grouted concrete masonry unit (CMU). The CMU core can be used for thermal energy storage.

AIS Prototype Design

[0064] As a proof of concept, a 24 in×24 in (60 cm×60 cm) AIS system was built. An illustration of the AIS system **900** is provided in FIG. **9**. As shown in FIG. **9**, the AIS system **900** comprises 2-in-thick (50.8 mm) extruded polystyrene (XPS) insulation **902**, **904** and three 2-inch-wide U-channel aluminum foils **906**, **908**, **910**.

[0065] Aluminum foils **912**, **914** with 24 in×24 in and 10 mil in thickness (60 cm×60 cm and 0.254 mm thickness) were placed on both sides of the XPS insulation **902**, **904**. TABLE 2 shows material properties of the XPS insulation **902**, **904** and the aluminum foils **912**, **914**.

TABLE 2

Material Properties of the Main AIS Components

Material	Thermal conductivity (W/m · K)/(Btu-in/hr · ft^2 · ° F.)	Heat capacity (J/kg · K)/ (Btu/(lb · ° F.))	Density (kg/m^3)/ (lb/ft^3)
Aluminum foil	220/1526	900/0.215	2700/168.55
XPS	0.029/0.201	1470/0.351	28.6/1.785

[0066] The AIS system **900** is at an R-low state when the U-channel aluminum foils **906-910** engage with the top and bottom aluminum foils **912**, **914** and create a thermal bridge between them that increases the effective thermal conductivity of the AIS system. Conversely, the R-high state is attained when the U-channel aluminum foils **906-910** are disengaged from the top and bottom aluminum foils **912**, **914**. An air gap of 3 inches (76.2 mm) is left in the middle of the AIS system **900** to allow the U-channel aluminum foils **906-910** to engage (R-low) and disengage (R-high) on demand.

Laboratory Heat Flow Meter Test

[0067] Another AIS system **1000** is shown in FIG. **10**. This AIS system **1000** was tested in a heat flow meter (HFM) apparatus to investigate the impact of the individual AIS components on the system. Two pieces **1002**, **1004** of 10.5"×24" (26.67 cm) XPS insulation were spaced 3" apart in the middle to leave an air gap **1006** to give space for the U-channel metal strips **1008**, **1010**, **1012** for movement.

[0068] The AIS system **1000** was tested with 10 mil-thick (0.254 mm) aluminum foils **1014**, **1016** covering both sides of the insulation. The U-channel metal strips **1008-1012** were removed from the air gap **1006** to create the R-high state. Finally, the U-channel metal strips **1008-1012** were placed in the air gap **1006** and in contact with the aluminum foils **1014**, **1016** to create a thermal bridge and R-low state.

[0069] The HFM has the capability of taking localized heat flux measurements. An illustration is provided in FIG. **11** for a layout **1100** for the HFM. The HFM comprises a plurality of sensors **1102-1130**. Each sensor has a measuring area of 3"×3" (76.2 mm×76.2 mm) and are arranged as shown in FIG. **11**. Sensors **1110**, **1112**, **1114**, **1116**, **1118**, **1120** and **1122** measure the heat flux and thermal conductivity of the AIS system from left to right either on the XPS and aluminum foil composite or the AIS strip in the middle. Sensors **1102**, **1106**, **1116**, **1126** and **1130** measure the heat flux and thermal conductivity of the AIS strip in the middle.

Simulation Design

[0070] Simulations were run to reproduce the HFM measurement for validation purposes and to further optimize the AIS specifications used in the wall design and construction. An AIS system with 1" thick XPS and 10 mil aluminum foils was simulated and validated with the HFM test. The COMSOL Multiphysics 6.0 Heat Transfer and Surface-to-Surface Radiation modules were used to compute the effective heat flux and nominal R-values at the R-low and R-high states. The boundary conditions on the sides of the test samples were set to 12.8° C. and 35° C. just as these were set in the HFM. Based on parametric simulations, the thickness of the aluminum foils and the number of the aluminum U-channels that more effectively enabled R-low and R-high were set.

Results and Discussion

[0071] This section compares the simulation and experimental results for validation purposes. In addition, HFM experimental measurements and extrapolated simulation results are described and discussed herein to show the capability of the R-low and the R-high ratios under different parameters. Finally, the newly constructed wall is discussed.

Validation of Simulation Results

[0072] Heat flux measurements of the test sample were recorded and compared with simulation values. Heat flux measured values by sensors **1110-1122** of FIG. **11** were compared with the average heat flux simulation results every 3" (76.2 mm) across the mid-section from left to right for the R-low case with the 1" thick XPS foam covered with 10 mil aluminum foil at the top and the bottom. Sensor **1110** covers the distance from 1.5"-4.5" (38.1 mm-114.3 mm) from the left, while sensor **1112** spans 4.5"-7.5" (114.3 mm-190.5 mm) from the left, and so on. Sensor **1116** represents the heat flux measurement at the center and around the symmetry line of the setup.

[0073] FIG. **12** shows that simulation results have good agreement with the experimental data. The average percent error between the measured and simulated results was 4.4%.

Laboratory Test and Extrapolated Simulation Results

[0074] The AIS test specimen was built with materials and specifications discussed above. To improve the accuracy of the HFM measurement, silicone mats with known thermal conductivity were placed at the top and bottom of the AIS. Additionally, ¾" (19 mm) thick XPS foam is placed on the top of the AIS, and the heat flux values and their respective thermal conductivity of the AIS system were measured in three steps. As the first step in measuring the R-high state, the three aluminum strips in the middle (e.g., in the air gap) were not connected to the top and bottom layers of the aluminum foils. To differentiate the effects of radiation from heat conduction due to thermal bridging of the aluminum strips, this step was repeated with aluminum foils having an inner side of dark paint and a shiny surface at the middle air gap. The last test conducted was the R-low case with the three aluminum strips in contact with the aluminum foils.

[0075] The heat flux measurements of the AIS system together with the silicone mats and ¾" XPS were measured together. While computing the R-values of the AIS system, the R-values of the mats and the additional XPS board are subtracted as shown in mathematical equation (1).

$$R_{AIAS} = \frac{l \cdot \Delta T}{q_{tot}} - 2R_{mat} - R_{XPS} \tag{1}$$

[0076] TABLE 3 shows the heat flux measurements from each sensor in the HFM, the average heat flux of the AIS mid-section, and the computed R-values of the AIS system under different R-states (R-high and R-low).

TABLE 3

Heat Flux Measurements by Each Sensor in the HFM, Average Heat Flux in Mid-section, and R-values of the AIS

R-state	Heat flux measurements in each sensor (FIG. 6(b)) (W/m^2)/(Btu/sq. ft. hr)							Average heat flux across mid section (W/m^2)/(Btu/sq. ft. hr)	R$_{AIS}$ (° F. · ft^2 · h/Btu)/(K · m^2/W)
R-low				50.75				25.07	1.34
				16.1				7.92	0.236
			24.58	48.06	29.35				
			7.79	15.2	9.3				
	17.89	18.42	24.69	48.49	29.60	18.36	18.03		

TABLE 3-continued

Heat Flux Measurements by Each Sensor in the HFM, Average Heat Flux in Mid-section, and R-values of the AIS

R-state	Heat flux measurements in each sensor (FIG. 6(b)) (W/m^2)/(Btu/sq. ft. hr)							Average heat flux across mid section (W/m^2)/(Btu/sq. ft. hr)	R$_{AIS}$ (° F. · ft^2 · h/Btu)/(K · m^2/W)
	5.67	5.84	7.89	15.4	9.38	5.82	5.72		
			23.87	50.49	29.67				
			7.57	16	9.41				
				48.90					
				15.5					
R-high and inner Al foil surface dark painted				24.48				18.95	2.99
				7.76				6.01	0.527
			19.97	24.88	19.52				
			6.63	7.89	6.12				
	17.51	16.91	20.66	24.10	19.94	16.32	17.26		
	5.55	5.36	6.55	7.64	6.32	5.37	5.47		
			20.64	25.77	20.29				
			6.54	8.17	6.43				
				23.70					
				7.51					
R-high				13.06				12.95	4.19
				4.14				4.11	0.738
			13.23	13.03	13.16				
			4.19	4.13	4.17				
	12.83	12.89	13.25	13.10	13.08	12.63	12.88		
	4.07	4.09	4.21	4.15	4.15	4.0	4.08		
			13.13	13.28	13.24				
			4.16	4.21	4.2				
				13.16					
				4.17					

[0077] The hot and cold plate temperatures of the HFM were 35° C. and 12.8° C. with temperature differential (ΔT) of 22.2° C.

[0078] As shown in TABLE 3, the average heat flux, and their respective R values, for R-low, R-high with dark paint, and R-low with shiny surfaces were found to be 25.14 W/m^2 (R-1.34), 18.95 W/m^2 (R-2.99) and 12.95 W/m^2 (R-4.19), respectively.

[0079] A COMSOL Multiphysics simulation was run for identical material properties, geometry, and boundary conditions to compute the R-values of the AIS under R-low and R-high conditions. The simulation results were compared with the experimental results, and additional parameters were varied to optimize the R-high to R-low ratio. Two parameters, namely, the thicknesses of the rigid insulation and the aluminum foils, were varied. The XPS thickness was varied between 1" (25.4 mm), 1.5" (38.1 mm), and 2" (50.8 mm), and the thickness of the aluminum foils used was 10 mil and 20 mil foils. As shown in TABLE 4, the simulated and measured data agree well.

TABLE 4

Measured and Simulated R-values of the AIS System under R-low and R-high States.

Set up	R-values (° F · ft^2 · h/Btu)/(K · m^2/W)				
	Measured 1"	Simulated 1"	Simulated 1.5"	Simulated 2", 10 mil	Simulated 2", 20 mil
R-high	4.2/0.740	4.3/0.757	6.3/1.109	8.2/1.444	8.2/1.444
R-low	1.4/0.247	1.3/0.229	1.5/0.2641	1.5/0.2641	1.1/0.2641
R-high/R-low	3.0/0.528	3.3/0.581	4.2/0.740	5.5/0.969	7.5/1.321

[0080] The rigid foam provides R-4.3/in without the AIS. 20 mils (0.51 mm) aluminum foils were used with 2" (50.8 mm) rigid foam insulation to attain R-8.2 in the R-high and R-1.1 in the R-low states, which led to a Rmax/Rmin ratio of 7.5.

AIS Wall Design for Large-Scale Environmental Chamber Test

[0081] The previous sections showed that the R$_{max}$/R$_{min}$ ratio could be achieved based on HFM and simulation tests. In this section, a discussion is provided for a design of a scaled-up, automated wall to test a fast R-states' varying capability and the AIS durability. For ease of swinging between R-high and R-low, the fixed U-channels in the HFM test are replaced by movable flat pieces **1302**, **1304** and a pair of fixed U-channel **1306**, **1308** as shown in FIGS. **13A-13B**.

[0082] A 4 ft×8 ft (1.2 m×2.4 m) AIS system **1300** was designed to be tested under a Guarded Hot Box. The active insulation is constructed of pairs of aluminum sheets, aluminum U-channels **1306**, **1308** and moving aluminum pieces **1302**, **1304** to engage and disengage with the U-channels. The active insulation is placed in six equidistant positions and the remaining gap is filled with XPS foam. FIG. **13**A shows the R-low state where the flat pieces **1302**, **1304** are engaged with the U-channels **1306**, **1308** to create a thermal bridge and a higher heat flow through the AIS system **1300**. In The R-high state, with the lack of contact between the metal pieces creates a thermal break to allow a smaller amount of heat flow through the AIS system **1300** as shown FIG. **13**B.

[0083] The movement of the flat piece **1302** may be limited using stopper(s) **1310** during R-high states. Spring(s) **1312** is(are) placed between the stopper **1310** and flat piece **1302** to provide some tolerance in case that flat pieces **1302**, **1304** are not at the same distance from the U-channel leg(s) **1314**.

[0084] The control system uses a linear motion of the flat pieces **1302**, **1304** to engage/disengage with the U-channels **1306**, **1308**. The flat pieces **1302**, **1304** are suspended in a steel wire which is clamped to a shaft (not shown). The shaft is rotated using a DC motor and the wire clamped to the shaft converts the rotary motion into linear motion. The DC motor is controlled using the signal sent by the data acquisition system/controller based on the control logic and the sensor input from the thermistors connected at the surface of the AIS system **1300**. Also, it can be monitored in the Guarded hot Box for an extended period under different climate conditions and R-state schedules.

[0085] AIS selection criteria and AIS technologies evaluation procedures have been described. A solid-state thermal switch including mechanically moving metal strips combined with a rigid insulation concept was selected. A proof of concept of the design was constructed and tested in a heat flow meter apparatus with multiple sensors. The results obtained are used to calibrate a COMSOL model of the AIS system; the average percent error was 4.4%. A 2 in (50.8 mm) thick XPS integrated with 20 mil aluminum foils provides an R-high of 8.2 ft^{2}·° F·h/BTU (1.44 W^{2}·m/K) and an R-low of 1.1 ft^{2}·° F·h/BTU (0.19 W^{2}·m/K) ft^{2}·° F·h/BTU. Based on the disclosed technologies, a 4 ft×8 ft (1.2 m×2.4 m) AIS wall can be constructed and instrumented to monitor its performance.

[0086] FIGS. **14-15** provide illustrations of an active insulation system **1400** in an ON (or LOW-R) state and an OFF (or High-R) state. The active insulation system **1400** comprises a thermal masse **1490** sandwiched between two STS panels **1480**. Each STS panel **140** comprises the filler **1402**, **1404** that may include layers of thermally insulative material separated from each other by an open area (e.g., a through-hole or gap) **1410**. Thermal connector(s) **1412** is(are) disposed in the open area **1410**. The thermal connectors can include, but are not limited to, thermal switch(es) that is(are) made of a paramagnetic material, diamagnetic material and/or a ferromagnetic material with a high thermal conductivity k. Portions **1414**, **1416** of open area **1410** comprise air. The air facilitates movement of at least a portion of each thermal connector **1412**. The movement can include, but is not limited to, tilting, sliding, rotating and/or a translational movement.

[0087] At the ON (or Low-R) state shown in FIG. **14**, the thermal connector(s) **1412** create a thermal bridge **1450** that connect the thermally conductive panels **1406**, **1408** to each other. This connection enhances the heat flow through the active insulation system **1400** as shown by arrows **1440**, **1442**, **1444**, **1446**. The heat can flow from the STS panel to the thermal mass **1490**. The heat is stored in the thermal mass and may subsequently be caused to flow from the thermal mass through the other STS panel.

[0088] At the OFF (or High-R) state shown in FIG. **15**, the switchable thermal connector(s) **1412** will move so that an additional area **1500** is created in open area **1410** that fills with air. This additional area **1500** is referred to herein as a thermal gap. In effect, the thermally conductive panels **1406**, **1408** are disconnected from each other via the switchable thermal connector(s) **1412**. In effect, heat can no longer flow from the thermally conductive panel **1406** to thermally conductive panel **1408** through thermal connector(s) **1412** and into thermal mass **1490**.

[0089] Switching the active insulation system **1400** between the ON and OFF states is achieved using control circuitry **1420**. Control circuitry can include, but is not limited to, a process, a current source and/or electromagnet (s). The processor performs operations to cause the current source to selectively supply electric current to the electromagnet(s). The electromagnet(s) can include, but are not limited to, low voltage electromagnets such as 6 to 12 VDC electromagnets.

[0090] In the multiple thermal connector scenario, the thermal connectors **1412** can be triggered individually to have some thermal connectors ON and some thermal connectors OFF to achieve an R-value between High-R and Low-R. The active insulation system **1400** remains in the ON or OFF state even after the electromagnet(s) is(are) de-energized until it is reenergized to change the state of the active insulation system **1400**. Thus, energy is not needed to maintain the ON state or the OFF state of the active insulation system **1400**.

[0091] FIG. **17** provides an illustration of another active insulation system **1700** implementing the present solution. System **1700** comprises a thermal mass **1702**, a first STS panel **1704**, an optional second STS panel **1706**, and a control circuit **1708**. The difference between system **1700** and system **1400** is that the STS panel(s) is(are) at least partially located inside the thermal mass rather than external to the thermal mass.

[0092] Thermal mass **1702** can include, but is not limited to, a building structure (e.g., a concrete wall), and/or a phase change material. Each of the STS panels **1704**, **1706** can be the same as or similar to STS panel **260** of FIGS. **2-3**, **560** of FIGS. **5-6**, **760** of FIG. **7-8**, or **1600** of FIG. **16**. Control circuit **1708** can be the same as or similar to control circuit **220**, **222** of FIGS. **2-8** and/or control circuit **1420** of FIGS. **14-15**. Thermal connector(s) of the first STS panel **1704** is(are) switchable independent from any switching of thermal connector(s) of the second STS panel **1706**. The control circuit **1708** may be at least partially disposed internal or external to the STS panel(s) **1704**, **1706**.

[0093] FIG. **18** provides a flow diagram of an illustrative method **1800** for operating an STS panel (e.g., STS panel **260** of FIGS. **2-3**, **560** of FIGS. **5-6**, **760** of FIG. **7-8**, or **1600** of FIG. **16**). Method **1800** begins with **1802** and continues to **1804** where the STS panel is placed in an ON state. In the ON state, a first thermal bridge (e.g., thermal bridge **250** of FIG. **2**, **550** of FIG. **5**, **750** of FIG. **7**, or **1450** of FIG. **14**) is provided, by a first thermal connector (e.g., thermal connector **212** of FIG. **2**, **512** of FIG. **5**, **712** of FIG. **7**, or **1412** of FIG. **14**), between a first thermally conductive material (e.g., material **206** of FIG. **2**, **506** of FIG. **5**, **706** of FIG. **7**, or **1406** of FIG. **14**) and a second thermally conductive material (e.g., material **208** of FIG. **2**, **508** of FIG. **5**,

708 of FIG. **7**, or **1408** of FIG. **14**). The second thermally conductive material is spaced apart from the first thermally conductive material via a filler (e.g., filler **280** of FIG. **2**, **580** of FIG. **5**, **780** of FIG. **7**, or **1480** of FIG. **14**) formed of a first thermally resistive or insulating material.

[0094] In **1806**, heat is allowed to flow through the STS panel across the first thermal bridge created inside the STS panel. More specifically, the heat is allowed to flow from the first thermally conductive material across the first thermal bridge to the second thermally conductive material. The source of the heat can include, but is not limited to, a thermal mass such as concrete or a phase change material. The heat may optionally be allowed to flow from the STS panel to the thermal mass as shown by block **1807**. The heat may be stored in the thermal mass, and then subsequently allowed to pass back through the STS panel or through another STS panel as described herein.

[0095] Next optional blocks **1808**, **1810** involve: increasing an amount of heat flow through the STS panel (e.g., from the first thermally conductive material to the second thermally conductive material) by causing a second thermal connector (e.g., thermal connector **1602** of FIG. **16**) to provide a second thermal bridge (e.g., thermal bridge **1650** of FIG. **16**) therebetween; and decreasing the amount of heat flow through the STS panel by causing the second thermal connector to break the second thermal bridge and create a thermal gap, while the thermal bridge is still being provided by the first thermal connector.

[0096] Upon completing **1806** or **1810**, method **1800** continues with **1812** where the STS panel is caused to transition from the ON state to the OFF state in which the remaining thermal bridge being provided by the first thermal switch is broken. A thermal gap is provided by the first thermal switch when the STS panel is in the OFF state. This thermal gap is used in **1814** to prevent the heat from continuing to flow through the STS panel (e.g., from the first thermally conductive material to the second thermally conductive material) when the solid-state thermal switch panel is in the OFF state. This movement can comprise tilting, rotating or translational movement in an open area of the filler. Subsequently, method **1800** continues with **1816** where it ends or other operations are performed.

[0097] The invention as shown in the drawings and described in detail herein disclose arrangements of elements of particular construction and configuration for illustrating preferred embodiments of structure and method of operation of the present invention. It is to be understood however, that elements of different construction and configuration and other arrangements thereof, other than those illustrated and described may be employed in accordance with the spirit of the invention, and such changes, alternations and modifications as would occur to those skilled in the art are considered to be within the scope of this invention as broadly defined in the appended claims. In addition, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting.

We claim:

1. A solid-state thermal switch panel, comprising:

a filler formed of a first thermally resistive or insulating material and having a first open area;

first and second layers of thermally conductive material that are spaced apart from each other, extend parallel to each other, and sandwich the filler such that the first open area extends from the first layer of thermally conductive material to the second layer of thermally conductive material; and

a first thermal connector disposed in the first open area (a) so as to reside between and be spaced apart from the filler, and (b) so as to reside between and be in contact with the first and second layers of thermally conductive material;

wherein the first thermal connector is switchable between a first position in which a thermal bridge is created thereby to allow heat transfer between the first and second layers of thermally conductive material, and a second position in which the thermal bridge is broken and a thermal gap is created by the first thermal connector to prevent said heat transfer between the first and second layers of thermally conductive material.

2. The solid-state thermal switch panel according to claim **1**, wherein the first thermal connector is switchable between the first and second positions by tilting, rotating or translational movement.

3. The solid-state thermal switch panel according to claim **2**, wherein the first thermal connector comprises: a first portion having a first end suspended in the open area of the filler and a second end connected to the first layer of thermally conductive material; and a second portion having a third end suspended in the open area of the filler and a fourth end connected to the second layer of thermally conductive material.

4. The solid-state thermal switch panel according to claim **3**, wherein the first thermal connector is switchable between the first and second positions by tilting or rotating of the first end of the first portion thereof that is suspended in the open area.

5. The solid-state thermal switch panel according to claim **2**, wherein the first thermal connector is switchable between the first and second positions by translational movement of the first portion thereof towards and away from a second portion thereof.

6. The solid-state thermal switch panel according to claim **1**, wherein the first thermal connector comprises a ferromagnetic material, a diamagnetic material or a paramagnetic material configured to facilitate switching of the first thermal connector using at least one electromagnet.

7. The solid-state thermal switch panel according to claim **1**, further comprising a second thermal connector disposed in the first open area that is switchable between two positions independent from any switching of the first thermal connector between the first and second positions.

8. The solid-state thermal switch panel according to claim **1**, wherein a second open area is provided with the filler.

9. The solid-state thermal switch panel according to claim **8**, wherein another thermal connector is disposed in the second open area so as to reside between and be spaced apart from the filler, and so as to reside between and be in contact with the first and second layers of thermally conductive material.

10. The solid-state thermal switch panel according to claim **9**, wherein switching of the another thermal connector is controllable independent from any switching of the first thermal connector.

11. The solid-state thermal switch panel according to claim **1**, wherein the filler comprise a second thermally resistive or insulating material and the first open area comprises a gap between the first and second thermally resistive or insulating materials.

12. An active insulation system, comprising:

a thermal mass;

a solid-state thermal switch panel positioned internal to the thermal mass or adjacent and in contact with the thermal mass, wherein the solid-state thermal switch panel comprises:

a filler formed of a first thermally resistive or insulating material and having a first open area;

first and second layers of thermally conductive material that are spaced apart from each other, extend parallel to each other, and sandwich the filler such that the first open area extends from the first layer of thermally conductive material to the second layer of thermally conductive material; and

a first thermal connector disposed in the first open area (a) so as to reside between and be spaced apart from the filler, and (b) so as to reside between and be in contact with the first and second layers of thermally conductive material, wherein the first thermal connector is switchable between a first position in which a thermal bridge is created thereby to allow heat transfer between the first and second layers of thermally conductive material, and a second position in which the thermal bridge is broken and a thermal gap is created by the first thermal connector to prevent said heat transfer between the first and second layers of thermally conductive material; and

a control circuit configured to control switching of the first thermal connector between the first and second positions.

13. The active insulation system according to claim **12**, wherein the thermal mass comprises concrete, a phase change material or a container filled with a fluid.

14. The active insulation system according to claim **12**, further comprising a second solid-state thermal switch panel that is positioned such that the thermal mass is sandwiched between the first and second solid-state thermal switch panels.

15. The active insulation system according to claim **14**, wherein the first thermal connector of the first solid-state thermal switch panel is switchable independent from any switching of a second thermal connector of the second solid-state thermal switch panel.

16. The active insulation system according to claim **12**, wherein the control circuit is at least partially disposed internal to the first solid-state thermal switch panel.

17. A method for operating a solid-state thermal switch panel, comprising:

placing the solid-state thermal switch panel in an ON state in which a first thermal bridge is provided, by a first thermal connector, between a first thermally conductive material and a second thermally conductive material spaced apart from the first thermally conductive material via a filler formed of a first thermally resistive or insulating material;

allowing heat to flow from the first thermally conductive material across the first thermal bridge to the second thermally conductive material;

causing movement by at least a portion of the first thermal connector to transition the solid-state thermal switch panel from the ON state to an OFF state in which the first thermal bridge is no longer being provided by the first thermal connector; and

using a first thermal gap created by the first thermal connector to prevent the heat from continuing to flow from the first thermally conductive material to the second thermally conductive material when the solid-state thermal switch panel is in the OFF state.

18. The method according to claim **16**, wherein the movement of the at least a portion of the thermal connector comprises by tilting, rotating or translational movement in an open area of the filler.

19. The method according to claim **16**, further comprising increasing an amount of heat flow from the first thermally conductive material to the second thermally conductive material by causing a second thermal connector to provide a second thermal bridge therebetween.

20. The method according to claim **19**, further comprising decreasing the amount of heat flow from the first thermally conductive material to the second thermally conductive material by causing the second thermal connector to break the second thermal bridge and create a second thermal gap, while the first thermal bridge is still being provided by the first thermal connector.

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